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Journal Coordinators
- **Ir Julian LEE**, Email: cflee@hkcic.org
- **Dr. James WONG**
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- **Ms. Grendy LAM**

Contact Details
Construction Industry Council
15/F, Allied Kajima Building
138 Gloucester Road
Wanchai, Hong Kong
Tel: (852) 2100 9000
Fax: (852) 2100 9090
Website: www.hkcic.org

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About Construction Industry Council

The Construction Industry Council (CIC) was formed on 1 February 2007. CIC consists of a chairman and 24 members representing various sectors of the industry including employers, professionals, academics, contractors, workers, independent persons and Government officials.

The main functions of CIC are to forge consensus on long-term strategic issues, convey the industry's needs and aspirations to the Government, as well as provide a communication channel for the Government to solicit advice on all construction-related matters. In order to propagate improvements across the entire industry, CIC is empowered to formulate codes of conduct, administer registration and rating schemes, steer forward research and manpower development, facilitate adoption of construction standards, promote good practices and compile performance indicators.

CIC has set up Committees to pursue initiatives that will be conducive to the long-term development of the construction industry. Further information is available on www.hkcic.org.

VISION

To drive for unity and excellence of the construction industry of Hong Kong.

MISSION

To strengthen the sustainability of the construction industry in Hong Kong by providing a communications platform, striving for continuous improvement, increasing awareness of health and safety, as well as improving skills development.

EXECUTIVE DIRECTOR's MESSAGE

Welcome to the second issue of the Construction Industry Council (CIC)'s research journal Innovation in Construction (iCON). Not only does it set out to be the research journal of the CIC's funded projects, but it also serves as the channel of communication between industry practitioners and researchers in the wider construction industry community. We look forward to hearing from both sides upon the publication of these innovative ideas and exciting findings. With emerging technologies and practices generated from this platform, we believe that Hong Kong's construction industry can be transformed into an even more competitive one.

Innovation is a key element in gaining the competitive edge. For this reason, encouraging the development and use of innovative technologies in the construction industry is one of the core functions of the CIC. In November 2014, we organised the biannual CIC Conference on the theme of "Construction Innovation and Safety Enhancement for the Betterment of Our Society", in which the lively discussions and exchanges are a testament to Hong Kong's growing appreciation of innovations and research applications. While industry players have warmed up to the increasing use of new technologies, there remains a series of challenges to wider adoption of innovations in the industry.

We cannot afford to grow complacent with our old ways and be left behind in this rapidly evolving World. Working with our steadfast industry and research partners, the CIC is optimistic about the prospect of correctly identifying and solving the remaining issues.

Hong Kong takes pride in becoming a regional and global leader in competitiveness. While Hong Kong's workers, with construction workers included, have always been well-known for working harder and faster than everyone else, in today's world, we also need to work smarter in order to spur productivity growth. Working smarter requires creative thinking, a strong investment in research and development, and a vibrant ecosystem in which new ideas are continually exchanged and tested.

To this end, the publication of iCON will become an important building block of this culture of innovation through research and development involving all stakeholders: government, academia, and industry. Every new issue of iCON is a step further towards this collaborative goal. We thank all of you who have taken this step together.

Ir Dr. TO Wing, Christopher
Executive Director
Construction Industry Council

EDITORIAL

On behalf of the Task Force on Research of CIC, I am delighted to introduce you this latest issue of "*Innovation in Construction*" (*iCON*), which disseminates the most updated and inspiring research findings generated from the CIC Research Fund. With a focus on construction technology, *iCON* 2 brings us the R&D concepts and progress in terms of innovative technologies in enhancing industry performance as well as optimising design and construction methods and efficiency.

The exclusive interview in this issue features Prof. Miroslaw J. SKIBNIEWSKI from the University of Maryland in the United States, a well-known professor and expert in construction automation and robotisation. Prof. SKIBNIEWSKI shares his views and insights on the automation development and translating innovative ideas into construction reality, particularly in the Hong Kong industry.

Running for two and a half years, some of the funded research projects has come to the harvest time for disseminating their research outcomes. The feature story of *iCON* 2 highlights the fruitful achievements of the recently completed project conducted by Prof. K.F. CHUNG's team. With the imminent adoption of the Structural Eurocodes in Hong Kong, Prof. CHUNG firstly provides an overview on the use of the Structural Eurocodes. Various opportunities in steel construction offered by steel materials and structural steelwork equivalent to those manufactured in accordance with European specifications are also manifested.

Apart from the completed project, interest findings of five on-going projects are covered in this issue. As part of his research in retrofitting reinforced concrete (RC) columns in Hong Kong to address seismic issues, Dr. WU Yufei introduces a more rational and accurate plastic hinge model for external jacketing with fiber reinforced polymer (FRP). Dr. P.L. NG and his research team share with us their brilliant concept of producing ultra-ductile waterproofing rendering from recycled plastic bottles. Dr. Ray SU is developing a convenient simplified model to assess the seismic performance of low-rise RC frames and high-rise RC wall buildings with or without transfer structures. Dr. Daniel CHAN's research attempts to develop statistical construction time prediction models for high-rise private building projects in Hong Kong and investigate the construction time performance (CTP). In this Journal his desktop taxonomic review is presented to examine the previously developed models and the current state of construction duration modelling methods. Last but not least, Ms. MAING MinJung, based on a preliminary study a typical building envelope type of a housing complex, reveals the impact of building envelope configurations on urban outdoor thermal environment between building towers.

It is exciting to see so many great ideas and remarkable research findings being unveiled to the industry through *iCON* 2. I must express my sincere appreciation to all the researchers and authors who have made significant contribution and input to this Journal. Hope you will find the content of this issue informative and inspirational. We always welcome your feedback on *iCON*, the CIC funded research projects, and more importantly, inspiring innovations for the benefit of our industry development.

Jimmy TSE, MH

Chief Editor

Chairman, Task Force on Research

Construction Industry Council

CIC
Research Funding Programme

The Construction Industry Council (CIC) was formed on 1 February 2007 in accordance with the Construction Industry Council Ordinance (Cap. 587). CIC encourages research projects that are directly related to the needs of the industry. Under the Ordinance, one of the main functions of CIC is to encourage research activities and the use of innovative techniques and, to establish or promote the establishment of standards for the construction industry.

CIC from time-to-time initiates research projects to meet the industry needs. These research projects initiated by CIC may contribute to policy formulation or technology advancement, preparation of references for promotion of good practices and improvement measures, collection and analysis of necessary information for comparative study on industry practices, collection of international practices on certain areas of construction works to facilitate reviewing industry-wide issues with a view to deriving local strategies, etc.

CIC also supports research projects initiated by Research Institutes which aim to benefit the local construction industry through practical application of the research outcomes. Invitations to Research Institutes for research proposals will be sent out twice each year, in March and September respectively. The research projects with high potential to obtain CIC's fund should have practical values or benefits to the Hong Kong construction industry at large e.g. collaborative research between universities and the industry pertaining to industry development. The cost-effectiveness and project implementation of the proposal will also be considered.

Feature Story

Construction Innovation For the Betterment of Our Industry

Exclusive Interview with an Industry Visionary - Prof. Miroslaw J. Skibniewski

Department of Civil & Environmental Engineering
A. James Clark School of Engineering
University of Maryland

Prof. Miroslaw J. Skibniewski is a Professor of Construction Engineering and Project Management at the University of Maryland in College Park, USA. He is the Editor-in-Chief of Automation in Construction, a well-known international research journal publishing innovative and breakthrough studies on information technologies, automation and robotisation in the construction industry. As an expert specialising in construction automation with extensive research and practical experience, Prof. Skibniewski was invited to deliver a speech at the CIC Conference 2014 on 28 November 2014, sharing with us the Advances in Construction Automation and Robotics. During his short stay in Hong Kong, we seized this valuable opportunity to have an exclusive interview with Prof. Skibniewski seeking his views and insights on the automation development as well as the implementation of innovations in the construction industry, in particular the Hong Kong industry.

Every innovative idea needs the right ingredients to flourish.

Innovative Technologies Available in Construction

Hong Kong faces a shortage of skilled workers in the construction sector, with projects in Macau drawing workers away. In the meantime, ageing workforce and the escalating construction volume may further widen the gap between supply and demand of construction manpower. The construction industry has taken a wide range of initiatives to relieve the situation, one of which is the promotion, development and application of new technologies to undertake or assist human's works in various construction processes.

Being the Editor-in-Chief of Automation in Construction for years, Prof. Skibniewski has witnessed the generation, study and application of plenty creative ideas in the construction industry. "In 1920, the word 'Robot' was firstly coined by writer, Karel Čapek. In Czech, 'Robota' means 'heavy, dirty work'. 'Robot' is therefore a machine that was supposed to perform 'Robota'," Prof. Skibniewski shared with us the origin of Robot. He pointed out that the construction industry had been showing enormous creativity by adopting various types of construction machinery to enhance productivity and to deal with heavy, dirty, and dangerous works such as excavation and lifting of heavy objects.

However, manual control is still required to different extent in order to reduce the risk of casualties as well as to handle changing conditions in a construction site. Construction Automation only emerged fully in the 1980s when Robotics and Automation in Construction (RAC) became one of the most important research areas in the field of service robotics. Automated machines and robots for construction have been developed and currently there are already several types of robotics being applied for various construction activities, such as the concrete finishing, steel frame welding, pavement laying, demolition, etc. In recent years, R&D in RAC area has shifted the focus from machinery to information technologies, including on-site sensory data acquisition and processing, human operators' field safety and security, RFID chip-based process control and monitoring, automated inventory and shop-keeping.

Right Ingredients for Successful Innovations in Construction

Prof. Skibniewski pointed out that Robotics and Automation is a highly developed technology but its use in construction is rather limited as compared to other manufacturing industries due to various reasons. "Every innovative idea needs the right ingredients to flourish," he explained. "At the first place, the technology should be user-friendly and the workforce have to be well-trained to make the most of the technology. We will also need the right working environment and the ability to acquire and process data to produce necessary information for the construction tasks." More importantly, the industry should not overlook the technology's integration with both the upstream and downstream construction processes. He suspected that the construction industry had not yet equipped itself with enough and right ingredients for many of the automation and robotic techniques. Consequently, the available techniques could not be widely applied, nor could the adopted techniques be fully and economically utilised in the construction sector.

The importance of having all the right ingredients can be shown in the example of the Chirp-Spread-Spectrum (CSS)-based real-time location technology, which has been studied and pilot tested in some local construction projects. The system is designed for multiple purposes including efficient project management, real-time site hazard detection and safety monitoring, and so on. On one hand, many benefits have been demonstrated in

Large infrastructure or series of building projects are apparently the ideal target for automation.

site trials, such as fast tracking of equipment, materials, vehicles and individuals working in or visiting the construction site, generation of warning signals to avoid accidents, etc. On the other hand, some limitations have also been revealed. One problem is the workers' strong reluctance to carry a tracking device. Besides, the complex working environment of construction site also affects the CSS signal propagation due to obstacles on site.

Today, the majority of our effort in implementing robotics and automation in construction should not only be paid on designing technologies but also re-engineering the project site and restructuring the work tasks to meet the capabilities of the technology. Otherwise the technology would simply be a demonstration if the site itself is not even ready for it. Prof. Skibniewski supplemented that such redesigning might require new design or construction methods. He further elaborated with an example regarding how the project site or construction process should be redesigned. "Currently we mainly rely on scaffolders to carry out surface applications for buildings. However if a machine can climb by itself like a spider i.e. the 'spider' technology and conduct relevant works, manpower can be saved and the risk of persons falling from height can thereby be reduced. Applying one core technology, a family of construction tasks can be accomplished, Prof. Skibniewski advocated. This would lead to substantial improvement of efficiency and safety in the entire construction process.

Construction Innovations at the Frontier

When being asked the most impressive innovation in construction, Prof. Skibniewski reckoned that it is necessary to categorise the innovations into blue sky ideas and practical solutions. Prof. Skibniewski opined that the idea of "Swarming Micro Robots" is an impressive blue sky idea which may revolute how buildings are built. "Imagine when several hundred thousand micro robots are employed in the construction of a building, a hundred of them are assembling the underground structure, another hundred are in the superstructure and finishing the floors." Although it was hard to predict when they would be adopted, he emphasised that eventually this would happen. "We couldn't possibly imagine 20 years ago holding a tablet in people's hand and dealing with something called wireless internet."

Prof. Skibniewski also shared with us a technology which was once an imagination but is now being applied in construction, i.e., 3D printing. At no time would we ever imagine that the building construction could be integrated with printing technology, while nowadays construction materials such as concrete could be injected through an onsite 3D printer to build a 5-storey residential house. Same may apply to the Autonomous Robots that can sense and read about the environment for real-time measurement of the working conditions' quality. Additionally, they can be equipped with an in-built decision-making mechanism. "Although there are still a number of issues to be solved, its implementation on sites is at hand," Prof. Skibniewski added.

The Journey towards Fully Automated Construction

"30 years ago like many other people, I thought the construction industry is only 30 years away from 'full automation'." Prof. Skibniewski mentioned, "Pioneers in Japan have indeed demonstrated its feasibility. Certain construction processes are fully automated. Having said that, due to budget constraints, approximately 40% of the construction work in the country still has to be done by humans in traditional ways."

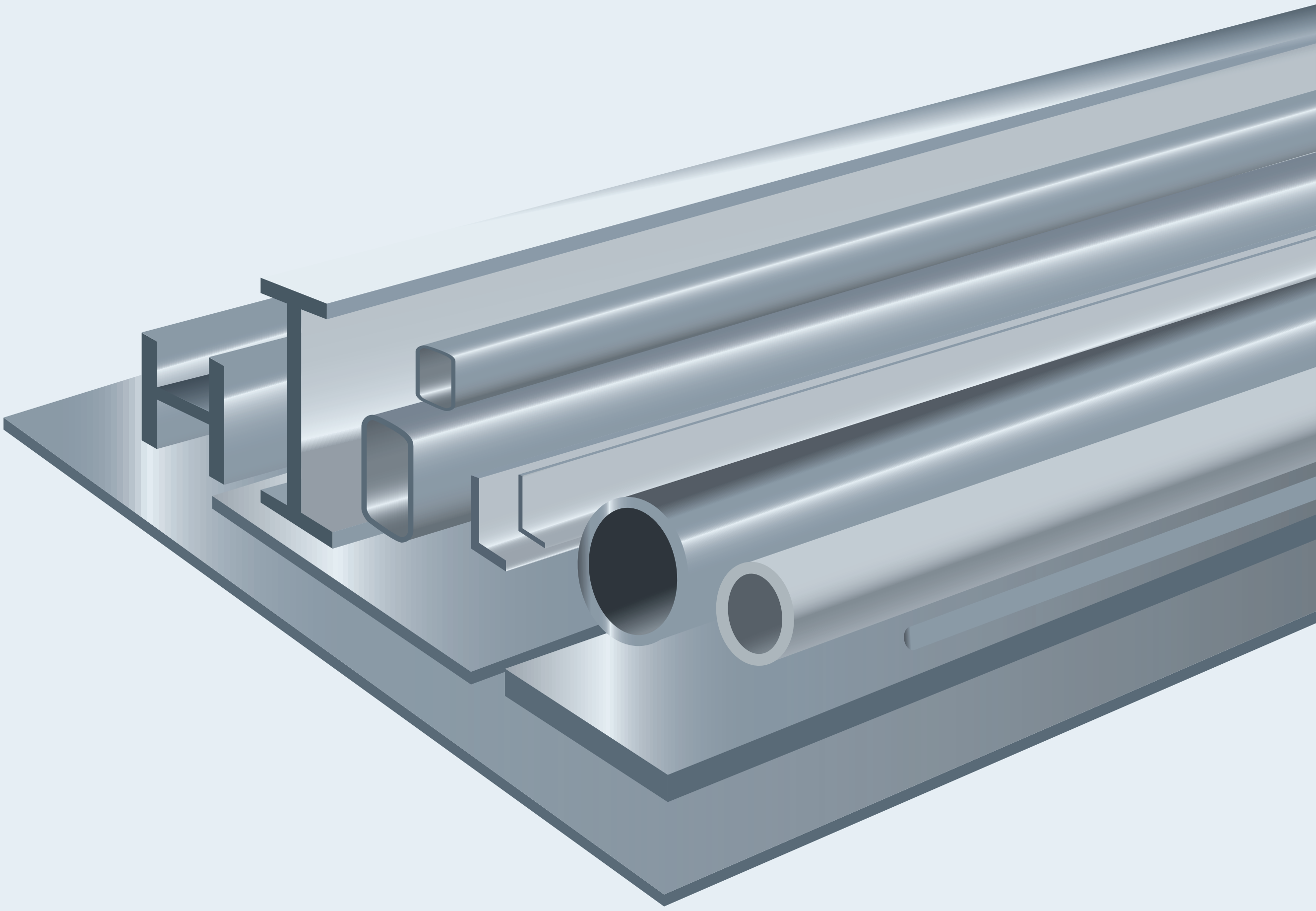
Apart from the concerns on cost, the construction industry's fragmented nature remains an obstacle in the path of full automation. The project-based industry is fragmented both "horizontally" in terms of the disciplines and trades (i.e. architectural, structural mechanical and electrical) and "vertically" in terms of a project life cycle (i.e. planning and design, construction, commissioning and operation). "It's a global problem," Prof. Skibniewski stressed, "together with the conventional design-bid-build procurement model of the industry as well as the regulatory environment, which are holding back innovations in our industry."

Despite all the hurdles lying ahead, it is still possible for some particular projects to realise fully automated construction. Prof. Skibniewski believed that the larger the project, with more repetitive and larger volume of works, the easier it would be to implement automation. "If the project is of low volume and requires a lot of sensing and reasoning, it's probably not a good competitor for automation because it will be very costly and inefficient." Prof. Skibniewski stressed. In Hong Kong, the majority of construction firms are either medium-sized or small-sized and investing in advanced technologies such as robots will greatly reduce their liquidity. From their perspective, it is still risky to invest in innovation on loans. As a result, large infrastructure or series of similar building projects flush with large volume, repetitive tasks are apparently the ideal target for automation.

"There is a wide spectrum of different tasks ranging from highly possible where automation will be adopted very soon to virtually impossible to be conducted by machines," Prof. Skibniewski concluded. "But ultimately the industry will pick up, lift off and carry this development forward to a much greater height. It will not only happen in Japan but I'm sure in Hong Kong, and in other countries if the benefits of robotics and automation are realised," he delivered to us his strong and positive belief in the future of construction automation.

The interview ended up with Prof. Skibniewski's anticipation towards the construction automation as well as the future development of the Hong Kong construction industry. Local construction professionals and practitioners are indeed very active and pioneering in promoting and adopting innovative techniques in our own industry. We could still remember clearly the rounds of applauses and the lively discussions at the CIC Conference, during which Prof. Skibniewski and other invited speakers shared with us their valuable insights in adopting new technologies in construction. Through this follow-up in-depth interview exchange with Prof. Skibniewski, we wish to raise confidence and inspire our local industry practitioners. At this turning point of the industry transformation, it is our decision to be more open-minded towards the application and implementation of advanced technologies, and to work together to engineer our future Hong Kong with innovation and excellence for all to benefit.

Research and Development on Design and Constructiion to Structural Eurocodes using Equivalent Steel Materials



Research and Development on Design and Construction to Structural Eurocodes using Equivalent Steel Materials

K.F. Chung[1,3,*], M.C.H. Yam[2,3] and H.C. Ho[1,3]

[1] *Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong*
[2] *Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong*
[3] *The Hong Kong Constructional Metal Structures Association, Hong Kong*

The Hong Kong Constructional Metal Structures Association was established in July 2010, and one of its primary objectives is to promote effective steel construction in Hong Kong and neighbouring cities in the Pearl River Delta Region. The Association is supported by members from universities, consulting firms, construction companies and representatives from government departments and professional bodies. Owing to abundant and steady supply of quality Chinese steel materials in the Region, there is an industrial-wide urge to employ Chinese steel materials and structural steelwork on local construction projects. With the imminent adoption of the Structural Eurocodes in Hong Kong and a number of Asian countries, it is highly desirable to facilitate design and construction engineers in Hong Kong to work effectively to Structural Eurocodes using Chinese steel materials.

With the support of the Chinese National Engineering Research Centre for Steel Construction and other leading industrial and professional organisations in China and overseas, a Professional Guide entitled "*Selection of Equivalent Steel Materials to European Steel Materials Specifications*" was prepared to provide technical guidance on the use of steel materials manufactured to national materials specifications of Australia / New Zealand, China, Japan and U.S.A.. Moreover, with the support of the Construction Industry Council, a Technical Guide entitled "*Effective Design and Construction to Structural Eurocodes: EN 1993-1-1 Design of Steel Structures*" was compiled to provide technical guidance on designing and constructing structural steelwork to Structural Eurocodes using equivalent steel materials, especially when welded steel sections such as I-sections, H-sections and cold-formed welded hollow sections are used.

This paper presents an overview on the use of the Structural Eurocodes as well as various opportunities on steel construction offered by steel materials and structural steelwork equivalent to those manufactured to European steel materials specifications. Key features of the two documents including the equivalence of steel materials and the corresponding material classification system as well as the use of European steel materials and their equivalent in structural design are thoroughly presented. Moreover, tabulated design data for rolled sections of steel materials complying to European specifications and welded sections of equivalent chinese steel materials are also described. Hong Kong design and construction engineers are encouraged to take full advantages offered by adoption of the Structural Eurocodes using equivalent chinese steel materials for construction projects in Hong Kong and neighbouring cities in the Region.

Keywords: Structures, steel materials, materials specification, steel design

1. ADOPTING STRUCTURAL EUROCODES IN HONG KONG

The Structural Eurocodes are a new set of European structural design codes for building and civil engineering works. Conceived and developed over the past 40 years with the combined expertise of the member states of the European Union, they are arguably the most advanced structural codes in the world. The Eurocodes are intended to be mandatory for European public works and likely to become the de-facto standard for the private sector - both in Europe and world-wide. The Eurocodes had been published as full European Standards (ENs) in 2007.

Owing to the withdrawal of British structural design standards in March 2010, the Works Department of the Government of Hong Kong SAR have been migrating to the Structural Eurocodes in stages for the design of

[*]kwok-fai.chung@polyu.edu.hk Prof. K.F. Chung

public works civil engineering structures while mandatory adoption of the Eurocodes commences in 2015. As a number of countries outside Europe, in particular, several Asian countries, have already adopted the Eurocodes for design and construction of building and civil engineering structures, there is a growing need for design and construction engineers in Hong Kong to acquire the new skills.

1.1. Organisation of the Eurocodes

A total of 58 parts of the Eurocodes are published under 10 area headings:

- Eurocode 0 - EN 1990: Basis of Structural Design
- Eurocode 1 - EN 1991: Actions on Structures
- Eurocode 2 - EN 1992: Design of Concrete Structures
- Eurocode 3 - EN 1993: Design of Steel Structures
- Eurocode 4 - EN 1994: Design of Composite Steel and Concrete Structures
- Eurocode 5 - EN 1995: Design of Timber Structures
- Eurocode 6 - EN 1996: Design of Masonry Structures
- Eurocode 7 - EN 1997: Geotechnical Design
- Eurocode 8 - EN 1998: Design of Structures for Earthquake Resistance
- Eurocode 9 - EN 1999: Design of Aluminium Structures

It should be noted that

i) the first two areas, namely, EN 1990 and EN 1991, are common to all designs - basis and actions;
ii) the other six areas, namely, from EN 1992 to EN 1996 and EN 1999, are material-specific - concrete, steel, composite steel and concrete, timber, masonry, aluminum; and
iii) the other two areas, namely, EN 1997 and EN 1998, cover geotechnical and seismic aspects.

Among the ten Structural Eurocodes, EN 1993-1-1 is considered to be one of the most important codes which contains advanced methodologies frequently referred by other Eurocodes, such as EN 1994 on steel-concrete composite structures, and EN 1992 on concrete structures as well as structural fire engineering of concrete, steel and steel-concrete composite structures (Chung, 2014). In general, EN 1993-1-1 provides general rules of steel structures as well as rules for buildings. Owing to the importance of these rules among the Eurocodes, design and construction engineers in Hong Kong should have good understandings on EN 1993-1-1 to take full advantages offered by the Eurocodes.

1.2 Basic considerations in selecting steel materials

According to the latest edition of the Steel Designers' Manual (2012), one of the key requirements in the choice of a particular steel material is that it should be fit for the intended application and the design conditions required. Hence, the following mechanical properties of the steel materials are considered to be very important:

- strength,
- ductility,
- toughness,
- through thickness properties,
- chemical compositions, and hence, weldability
- strength, stiffness and thermal expansion at elevated temperatures.

In addition, the steel materials should have a minimum service life which suits the expected environmental conditions, and hence, corrosion resistance is also important.

Various product forms of steel materials are summarised in Table 1 among many flat and long products. For structural applications, these products are inevitably cut to different sizes and shapes, and components are connected to one another through either bolts or welding in fabrication shops or on site. It should be noted that when a steel member is to be fabricated into components or structures, its ability to retain the required properties during fabrication should be clearly established. This ability is commonly assessed by the weldability of the steel material which depends heavily on the chemical composition of the steel material, such as the contents of Carbon (C), Sulphur (S), and Phosphorus (P). The welding processes and procedures adopted should also be compatible with the steel material chosen.

Table 1 Various products forms of steel materials

Structural steels	• plates • sections • hollow sections • sheet piles • solid bars • strips for cold formed open sections
Thin gauge strips	• strips for cold formed profiled sheetings
Connection materials	• stud connectors • non-preloaded bolted assemblies • preloaded bolted assemblies • welding consumables

2. USE OF EQUIVALENT STEEL MATERIALS

For many years, almost all steel structures in Hong Kong were designed to the British structural steel design code, BS5950, and all steel materials were specified correspondingly to British steel materials specifications such as BS4360. However, as early as the 1990s, non-British steel materials found their way to Hong Kong as well as to Singapore and other neighbouring cities in Southeast Asia. Occasionally, there were projects when contractors would use non-British steel materials, such as American, Australian, Japanese and Chinese steel materials. The changes ranged from merely using these materials for some members of temporary structures to replacement of complete beam-column frames of building structures. Over the years, many successful projects in Hong Kong benefited from good quality non-British steel materials, timely supply and delivery as well as improved structural economy. However, there were also a few bad examples of the use of non-British steel materials with inconsistent chemical composition, inadequate mechanical properties and lack of traceability.

2.1. Use of equivalent steel materials in Hong Kong

In the 2000s, owing to large fluctuations in the costs of steel materials in the global markets, Chinese steel materials became practical alternatives to British steel materials in a number of construction projects in Asia, in particular, in Hong Kong, Macau and Singapore. During the drafting of the "*Code of Practice for the Structural Use of Steel*" for the Buildings Department of the Government of Hong Kong SAR, i.e. the Hong Kong Steel Code from February 2003 to August 2005, it was decided necessary to devise a means to allow, or more accurately, to formalise, the use of Chinese steel materials as equivalent steel materials for structures which were originally designed to BS5950 (Chung, 2007). Various parts of Chapter 3 of the Hong Kong Steel Code provided basic principles and considerations for qualifying as well as accepting steel materials manufactured to the following national materials specifications:

- American standards,
- Australian / New Zealand standards,
- Chinese standards, and
- Japanese standards.

Moreover, a simple and practical classification system for non-British steel materials was also introduced in the Hong Kong Steel Code in which the design strengths of these steel materials depended on adequacy of materials specifications as well as effectiveness of quality control during their production.

2.2. Use of alternative steel materials in Singapore

A similar use of non-British steel materials was also formally adopted in Singapore with the issue of a technical guide entitled "*Design Guide on Use of Alternative Steel Materials to BS5950*" in 2008, and then its revised version entitled "*Design Guide on Use of Alternative Structural Steel to BS5950 and Eurocode 3*" in 2012 by the Building and Construction Authority of the Ministry of National Development.

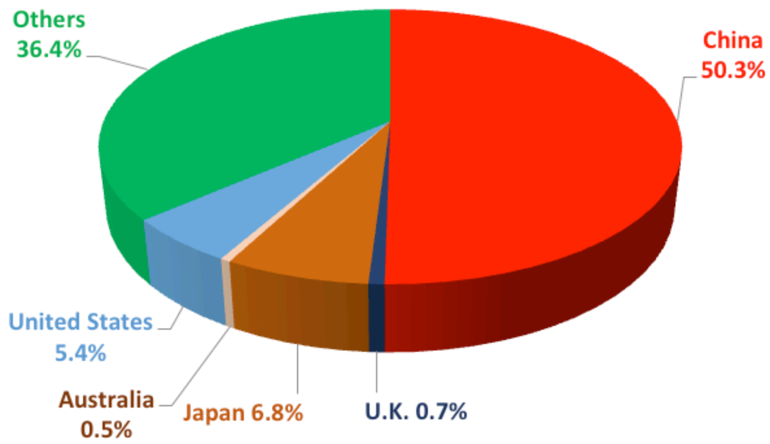
These Design Guides aimed to provide technical guidelines and design information on the use of non-British steel materials, and the classification system on various steel materials given in the Hong Kong Steel Code was adopted after minor modification. Under the provisions of these Design Guides, alternative steel materials not manufactured to European steel materials specifications may be allowed in structural design based on the Structural Eurocodes for construction projects in Singapore.

2.3. Abundancy of Chinese steel materials

Steel materials are international commodities which are commonly shipped thousands of miles from where they were manufactured to wherever there is a market. Based on the statistics archive of the World Steel Association (www.worldsteel.org), Table 2 presents the annual crude steel production of Australia, China, Japan, the United Kingdom and the United States of America from 1980 to 2014 together with total world production.

It is shown that Australia, Japan, the U.K. and the U.S.A. tend to maintain their annual crude steel production tonnages at a broadly constant level with a minimal growth as a whole. However, owing to the rapid development of the iron and steel industry in China since the 1980's, the steel production capacity increased markedly over the last 30 years. It should be noted that as a large number of steel mills in many parts of China upgraded their production facilities and commissioned new production plants, the annual crude steel production of China increased steadily from 37.1 million metric tons (mmt) in 1980 to 637.4 mmt in 2010, i.e. an increase of approximately 17.2 over a period of 30 years. Its annual crude steel production exceeded 100 mmt in 1996, 200 mmt in 2003, and then 500 mmt in 2008. Over 45% of the steel materials in the world have been produced in China since 2010.

As shown in Table 3, among the top ten major steel producing countries in 2014, the annual steel production of China reaches 882.7 mmt in 2014, accounting for 50.3 % of world production. Figure 1 also illustrates the proportions of the annual steel production of Australia, China, Japan, the U.K. and the U.S.A. in 2014. Hence, it is important for design and construction engineers in Hong Kong to be able to take advantages of the huge supply of Chinese steel materials.



Total world production is 1637.0 mmt

Figure 1 Annual crude steel production proportions of five countries of interest in 2014

Table 2 Annual crude steel production (mmt) of various countries of interest since 1980

Year	Australia	China	Japan	U.K.	U.S.A	World production
1980	7.6	**37.1**	111.4	11.3	101.5	568.5
1985	6.6	46.8	105.3	15.7	80.1	564.2
1990	6.7	66.4	110.3	17.8	89.7	616.0
1995	8.5	95.4	101.6	17.6	95.2	752.3
2000	7.1	128.5	106.4	15.2	101.8	848.9
2005	7.8	355.8	112.5	13.2	94.9	1146.6
2010	7.3	637.4	109.6	9.7	80.5	1428.7
2011	6.4	683.3	107.6	9.5	86.2	1536.2
2012	4.9	**716.5**	107.2	9.8	88.6	1546.8
2013	4.6	**779.0**	110.6	11.9	87.0	1582.5
2014	7.9	**822.7**	110.7	12.1	88.3	1637.0

Note: mmt denotes million metric tons.

3. EFFECTIVE USE OF EQUIVALENT STEEL MATERIALS

Shortly after its establishment in July 2010, the Hong Kong Constructional Metal Structures Association collaborated closely with the Macau Society of Metal Structures to explore various issues related to the equivalence of steel materials, and their impacts on construction projects in both Hong Kong and Macau. With the support of the Chinese National Engineering Research Centre for Steel Construction in Beijing, an Expert Panel on the Effective Use of Equivalent Steel Materials in Building Construction was established. A meeting of 12 steel experts from China, Hong Kong and Macau was held in early 2011 in Hong Kong to i) identify the needs of the local construction industry, ii) establish possible supply chains of equivalent steel materials, and iii) formulate recommendations for rectification. Consequently, an Expert Task Committee was established in March 2011 to collect technical information on both the chemical composition and mechanical properties of steel materials produced by European countries and the U.K., Australia, China, Japan, and the U.S.A for comparative analysis.

By September 2011, a number of steel materials specifications from various countries had been selected for further consideration according to their mechanical properties: yield strengths, tensile to yield strength ratios, elongation limits, toughness and weldability. The findings were presented to the Chinese Iron and Steel Association

Table 3 Major steel producing countries in 2014

Ranking	Country	Annual crude steel Production (mmt)	Proportion (%)	
1	China	822.7	50.3	
2	Japan	110.7	6.8	
3	U.S.A.	88.3	5.4	
4	India	83.2	5.1	
5	South Korea	71.0	4.3	84.6
6	Russia	70.7	4.3	
7	Germany	42.9	2.6	
8	Turkey	34.5	2.1	
9	Brazil	33.9	2.1	
10	Ukraine	27.2	1.7	
Total world production		1637.0		

and the Chinese Steel Construction Society in March 2012, and it was decided to expand the scope of the comparative analysis to cover steel materials under various delivery conditions as well as product forms. Moreover, a scientific and yet practical basis for gauging the equivalence of steel materials should be formulated. After a number of meetings of members of the Expert Task Committee as well as discussions and exchanges with experienced engineers and steel experts in Hong Kong, Macau and China, a draft of the Professional Guide entitled "*Selection of Equivalent Steel Materials to European Steel Materials Specifications*" was compiled in September 2013 for international consultation. During the Pacific Structural Steel Conference 2013 held in Singapore in October 2013, many experienced engineers and steel experts as well as technical representatives of national steel construction associations were invited to join the International Advisory Committee of the Professional

Guide. They provided valuable technical comments on the draft document as well as recommendations to the Expert Task Committee on the overall direction for further development of the Professional Guide. After receiving many favourable and constructive comments, the international consultation was concluded in April 2014, and the finalised version of the Professional Guide was compiled in July 2014 after incorporating all comments as appropriate.

Through the use of the Professional Guide, selected steel materials manufactured to modern materials specifications of Australia/New Zealand, China, Japan, and the U.S.A. are fully endorsed to be equivalent to those steel materials manufactured to European steel materials specifications including EN 10025, EN 10149, EN 10210 and EN 10219. Moreover, these equivalent steel materials must achieve full compliance with the requirements on material performance and quality assurance to EN 10025 as detailed in the Professional Guide. Consequently, these equivalent steel materials can be readily employed on construction projects in which structural steelwork is designed to EN 1993 and EN 1994. Hence, the Professional Guide provides an international level playing field for Chinese steel materials enabling them to compete directly with those steel materials from other countries for overseas construction projects.

In March 2015, the Professional Guide was jointly published by:

- the Hong Kong Constructional Metal Structures Association, Hong Kong SAR,
- the Macau Society of Metal Structures, Macau

SAR and

- the Chinese National Engineering Research Centre for Steel Construction, China.

The publication of the Professional Guide was also supported by:

- the Chinese Iron and Steel Association, China,
- the Construction Industry Council, Hong Kong SAR,
- the Civil Engineering Laboratory of Macau, Macau SAR and
- the Singapore Structural Steel Society, Singapore.

3.1. Equivalence of steel materials and their selection principles

Based on the experiences from the construction industry in Hong Kong and Singapore over the past 30 years as well as the use of both the "*Code of Practice for the Structural Use of Steel*" in Hong Kong and the "*Design Guide on Use of Alternative Structural Steel to BS5950 and Eurocode 3*" in Singapore over the past 8 to 10 years, the selection principles for equivalence of steel materials are established, and fully presented in the Professional Guide. Both material performance and quality assurance are considered to be essential requirements for equivalent steel materials, and key considerations of the selection principles have been identified as follows:

Material performance

- mechanical strength for structural adequacy,
- ductility for sustained resistances at large deformations,
- toughness in terms of energy absorption against impact, and
- chemical composition and weldability for minimised risks of crack formation in welds.

Quality assurance systems

- demonstrated compliance with acceptable reference standards,
- demonstrated compliance with material tests with sufficient sampling on both chemical composition and mechanical properties, and
- effective implementation of certificated quality assurance systems.

In order to demonstrate compliance with the material performance and the quality assurance requirements to European steel materials specifications, intensive routine testing should be conducted according to relevant materials specifications whilst the manufacturing process should be demonstrated as operating effectively under a Certified Quality Assurance System. A good example is a Certified Factory Production Control System to Appendix B.4 of EN 10025-1 which should have been effectively implemented, successfully certified and regularly monitored by an independent qualified Certification Body.

When performing rational selection of equivalent steel materials, the following considerations on mechanical properties and chemical composition should be taken in account of:

a) Mechanical strengths for structural adequacy

Both the minimum yield strength, R_{eh}, and the ultimate tensile strength, R_m, of the proposed steel materials should be directly adopted from their national materials specifications. It should be noted that the values of these two strength parameters depend heavily on both the dimensions of the coupons and the testing procedures. According to most European steel materials specifications, the values of both the minimum yield and the ultimate tensile strengths are gradually reduced when the plate thickness increases.

Owing to the different systems of strength grades among various national materials specifications, the values of both the minimum yield and the ultimate tensile strengths are often different to those of the corresponding European steel materials specifications. In these cases, re-design of structural steelwork is necessary.

b) Ductility for sustained resistances at large deformations

Ductility of steel materials is correlated approximately with their elongation limits, that is, the elongations of steel coupons at fracture in standard coupon tests. The values of the elongation limits depend heavily on the dimensions of the steel coupons and the testing procedures as well as the product forms of the proposed steel materials and the steel coupon sampling methods.

If a proposed steel material does not possess sufficient ductility as required by the relevant steel design codes, then the proposed steel material will not be accepted as an equivalent steel material.

c) Toughness in term of energy absorption against impact

Toughness is an important mechanical property of steel materials which is the resistance against brittle fracture, and is quantified as the amount of dissipated energy obtained from standard Charpy V-notch impact tests at various design temperatures. In general, if a proposed steel

material does not possess sufficient toughness as required in the relevant European steel materials specifications, then the proposed steel material will not be accepted as an equivalent steel material.
Nevertheless, the threshold values of this quantity are found to be related to both the stress levels and the thicknesses of the steel plates, and hence, these values are readily reduced according to actual applications of the steel materials using codified rules. In general, these values are often reduced significantly when thin plates are used, and in these circumstances, the steel materials are likely to be considered acceptable.

d) Chemical compositions and weldability to minimise risks of crack formation in welds

The contents of a number of chemicals should be kept to an optimal limit, such as Carbon (C), Sulphur (S) and Phosphorus (P) as their presence tend to reduce ductility, toughness and weldability as well as promote segregation at the same time. As a simple rule for hot-rolled structural steel sections, the maximum Carbon (C) content should not exceed 0.25% while the maximum Sulphur (S) content should not exceed 0.05%. Moreover, the maximum Phosphorus (P) content should not exceed 0.05%, which is further limited to 0.01 % when through thickness quality, i.e. Z quality, is specified.

The weldability of steel materials depends on the carbon equivalent value, CEV, which represents the combined effects of Carbon (C) and other chemical elements on the cracking susceptibility of the steel materials.

Hence, if any one of the contents of these non-beneficial chemicals of a proposed steel material exceeds the corresponding limit given in the relevant European materials specifications, then the proposed steel material will not be automatically accepted as an equivalent steel material. Moreover, if the CEV value of the proposed steel material exceeds the corresponding limit, then, the proposed steel material should be used with caution. Details of the welding procedures, such as interpass temperatures, should be modified according to the thicknesses of the steel materials. Furthermore, welding consumables shall match the steel types. Otherwise, testing for non-qualifying welding consumables should be undertaken.

3.2. Classification of steel materials

Given a satisfactory demonstration of both the material performance and the quality assurance during their manufacturing processes, steel materials with yield strengths from 235 to 690 N/mm^2 are classified as follows:

- *Class E1 Steel Materials*

Steel materials which are

i) manufactured in accordance with one of the Acceptable Materials Specifications listed in Appendix A of the Professional Guide with a fully demonstrated compliance on their material performance, and

ii) manufactured in accordance with an Acceptable Quality Assurance System with a fully demonstration of its effective implementation.

Thus, compliance with all the material requirements has been demonstrated through intensive routine testing conducted during the effective implementation of a certificated Factory Production Control System according to European steel materials specifications. The Factory Production Control System should be certified by an independent qualified certification body.

- *Class E2 Steel Materials*

Steel materials which are

i) manufactured in accordance with one of the Acceptable Materials Specifications listed in Appendix A of the Professional Guide with a fully demonstrated compliance on their material performance, and

ii) manufactured in accordance with an effectively implemented quality assurance system which is different to a Factory Control Production System.

Thus, the steel materials are manufactured in accordance with all the material requirements given in one of the Acceptable Materials Specifications, but without a certified Factory Production Control System in accordance with European steel materials specifications. In general, many steel manufacturers will have already established a form of quality assurance during the manufacturing processes, however, a high level of consistency in the material performance of the steel materials required in European steel materials specifications cannot be verified in the absence of a certified Factory Production Control System. Hence, as demonstration of the conformity of the steel materials is required, additional material tests with sufficient sampling should be conducted for various batches of supply to demonstrate full compliance to both the material performance and the quality assurance requirements. Refer to Section 3.2.3 of the Professional Guide for further details of additional materials tests.

- *Class E3 Steel Materials*

Steel materials for which it cannot be demonstrated they were

i) manufactured in accordance with any of the **Acceptable Materials Specifications** listed in Appendix A of the Professional Guide; nor

ii) manufactured in accordance with an **Acceptable Quality Assurance System**.

Hence, any steel material which cannot be demonstrated to be either Class E1 Steel Material or Class E2 Steel Material will be classified as Class E3 Steel Material, and the nominal value of yield strength of the steel material is limited to 170 N/mm^2 for structural design; no additional material test is needed in general. However, the design yield strength of the steel material may be increased if additional material tests with sufficient sampling have been conducted for various batches of supply before use.

Table 4 summarises the classification system applying to the various classes of steel materials. It should be noted that a newly defined factor, namely, the material class factor, γ_{MC} , is adopted as a result of the classification. Hence, the nominal values of the yield strength and of the ultimate tensile strength of Classes E1 and E2 Steel Materials are given as follows:

- Nominal value of yield strength
  $f_y = R_{eH} \; / \; \gamma_{MC}$ (Equation 1)

- Nominal value of ultimate tensile strength
  $f_u = R_m \; / \; \gamma_{MC}$ (Equation 2)

where

R_{eH} is the minimum yield strength to product standards;
R_m is the ultimate tensile strength to product standards; and
γ_{MC} is the material class factor given in Table 4.

It should be noted that

- Plastic analysis and design is permitted for Classes E1 and E2 Steel Materials assuming yield strengths not larger than 460 N/mm^2.

- For Classes E1 and E2 Steel Materials with yield strengths larger than 460 N/mm^2 but smaller than or equal to 690 N/mm^2, design rules given in EN 1993-1-10 should be used.

- Only elastic analysis and design should be used for Class E3 Steel Materials.

3.3. Quality assurance requirements to European steel materials specifications

In general, each steel manufacturer will have already established a form of quality assurance. However, in order to demonstrate compliance with the quality assurance requirements for steel materials equivalent to European steel materials specifications, a steel manufacturer should further establish a Factory Production Control System which is essential for demonstrating conformity of the steel material performances with European steel materials specifications. Moreover, in order to demonstrate effective implementation, the Factory Production Control System must be certified by an independent qualified certification body.

3.3.1. Factory Production Control System

A steel manufacturer should establish, document and maintain a Factory Production Control System (FPC) System to ensure conformity of his steel products with relevant materials specifications. In addition to a quality management system as well as an inspection system, he should carry out regular monitoring at least once a year as well as continuous surveillance. More importantly, he should perform material tests regularly in order to demonstrate full conformity of the proposed steel material with the relevant European materials specifications. All the material tests should be performed in accordance with relevant material testing standards listed in Section 3.2.3 of the Professional Guide.

Table 4 Classification system of various classes of steel materials

Nominal yield strength (N/mm^2)	Class	Compliance with material performance requirements	Compliance with quality assurance requirements	Additional material tests	Material class factor, γ_{MC} for yield strength, R_{eH}	Material class factor, γ_{MC} for ultimate tensile strength, R_m
$\geq$ 235 and $\leq$ 690	E1	Y	Y	N	1.0	1.0
	E2	Y	N	Y	1.1	1.1
	E3	N	N	N	-	-

3.3.2. Requirements for Factory Production Control System

The steel manufacturer is fully responsible for administrating the effective implementation of the FPC System during the manufacturing process of the steel material. He should draw up detailed technical specifications as well as effective quality assurance schemes which are appropriate to the steel material and the manufacturing process. He should also clearly define specific tasks and associated responsibilities of the tasks among various parties, and keep up-to-date documents defining the FPC System. Key tasks in the FPC System include:

- to identify procedures to demonstrate conformity of the material performances of the steel material at appropriate stages;
- to identify and record any incident of non-conformity; and
- to identify procedures to correct incidents of non- conformity.

The FPC System should achieve an appropriate level of confidence in the conformity of the material performance of the steel material, and this involves:

- documentation of procedures according to various requirements given in relevant technical specifications;
- effective implementation of these procedures;
- recording details of these procedures in operation and their results;
- use of these results to correct any deviation, repair effects of such deviation, correct any incident of non-conformity, and if necessary, revise the FPC System to rectify the cause of non-conformity.

It should also be noted that FPC procedures include some or all of the following:

- to specify and verify raw materials and constituents of the steel material;
- to conduct material tests on the steel material during manufacturing according to a pre-determined frequency;
- to conduct verification tests on finished products of the steel material according to a frequency which may be pre-determined in technical specifications, and adapted to the product and its conditions of manufacturing.

For further information on FPC Schemes, refer to Appendix B.4 of EN 10025-1.

4. EFFECTIVE STRUCTURAL STEEL DESIGN TO EUROCODES

With the financial support of the CIC Research Fund of the Construction Industry Council, a research and development project was undertaken by the authors at the Hong Kong Polytechnic University in June 2013 to provide technical guidance on effective design and construction of steel structures to the Structural Eurocodes. Hence, a Technical Guide entitled "*Effective Design and Construction to Structural Eurocodes: EN 1993-1-1 Design of Steel Structures*" was successfully compiled in November 2014 with technical supports from the Hong Kong Constructional Metal Structures Association and the Chinese National Engineering Research Centre for Steel Construction as well as the Steel Construction Institute and the Institution of Structural Engineers in the U.K., and the Institution of Civil Engineers Hong Kong Association. It should be noted that various drafts of the document had been critically reviewed by the Engineering Technology Committee of the Hong Kong Constructional Metal Structures Association as well as senior engineers and experts on steel construction.

In June 2015, the Technical Guide was published by the Construction Industry Council with support from the following organisations:

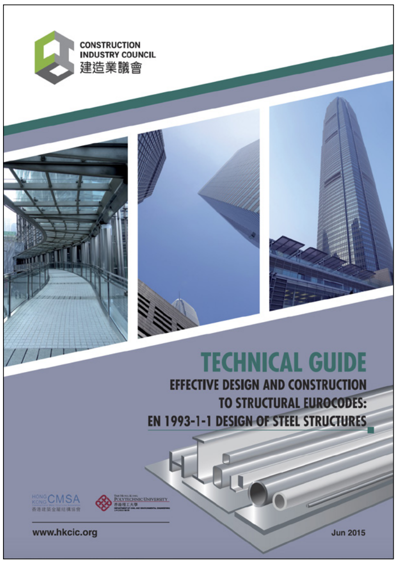
- The Hong Kong Polytechnic University,
- The Hong Kong Constructional Metal Structures Association,
- The Chinese National Engineering Research Centre for Steel Construction, and
- The Chinese Confederation of Roll Forming Industry.

The Technical Guide provides essential guidance on key design rules for structural steel design on both rolled and welded sections given in EN1993-1-1 as well as the associated U.K. National Annex together with relevant non-contradictory complementary information (NCCI). Moreover, all the Nationally Determined Parameters (NDPs) recommended by the Works Bureau of the Government of Hong Kong SAR provided in the updated design manuals of various government departments have been adopted. These items include load factors, loads, and methods for calculating certain loads, partial safety factors and advice where a choice in a design approach is allowed. Hence, technical information is presented in the context of the local construction industry, and references to prevailing regulations and codes of practice are made whenever necessary.

4.1. An Overview of Technical Guide

In general, all the key design rules given in EN1993-1-1 are described in the Technical Guide, and they are supplemented with explanatory notes and commentaries in the same sequence as found in the Eurocode:

- General
- Basis of design
- Materials
  - yield strengths
- Durability
- Structural analysis
  - section classification
- Ultimate limit states
  - resistance of cross-sections under single actions
  - resistance of cross-sections under combined actions
  - buckling resistance of members under single actions
  - buckling resistance of members under combined actions
- Serviceability limit states



In order to illustrate various design procedures for structural steel design, a total of 8 worked examples on cross-section properties and resistances as well as on buckling resistances of steel members are provided. Comprehensive design procedures for i) column members undergoing flexural buckling, ii) beam members undergoing lateral torsional buckling, and iii) beam-column members undergoing buckling under combined compression and bending are also provided. Detailed design information and parameters are also presented in a tabulated format for easy reference.

4.2. Design data for rolled and welded sections

In order to assist design and construction engineers to perform effective structural steel design, design data on section dimensions and properties as well as section resistances of a wide range of rolled and welded sections with practical steel materials are provided in the Technical Guide. Table 5 presents the types of rolled and welded sections covered in the document while typical cross-sections of these sections are illustrated in Figure 2. It should be noted that both rolled sections complying to European steel materials specifications and welded sections with equivalent Chinese steel materials have been incorporated as follows:

- *Rolled sections to European steel materials specifications*

a) All rolled I- and H-sections are assumed to be manufactured with steel materials to EN 10025 while their dimensions are manufactured to BS 4-1.

b) All hot-finished hollow sections are assumed to be manufactured with steel materials to EN 10210-1 while only selected hot-finished hollow sections specified in EN 10210-2 with a dimension larger than 100 mm are considered.

During preparation of tabulated design information, all of the rolled sections are assumed to be Class E1 Steel Materials with a material class factor, γ_{Mc}=1.0 as discussed in Section 3.2. Moreover, section resistances of all these sections with common steel grades, i.e. S275 and S355 steel materials, are tabulated in a systematic manner for practical design. Table 6 summarises various design information provided for the rolled sections covered in the document, and a total of 18 Design Tables have been compiled covering 234 rolled sections in two different steel materials.

- *Welded sections to Chinese steel materials specifications*

a) During preparation of the tabulated design information, all welded I- and H-sections are fabricated with steel materials to GB/T 700 and GB/T 1591 with standard thicknesses. It is envisaged that with a rational combination of these plate thicknesses in the flanges and the webs of the sections to GB/T 709, a series of welded sections with similar section depths and flange widths are readily manufactured covering a wide range of section properties and resistances for practical design. These ranges of section properties and resistances are similar to those rolled sections in the same series of section designations.

Table 5 Ranges of rolled and welded sections

Rolled sections **S275 and S355**	**Welded sections** **Q235, Q275, Q345 and Q460**
Rolled I-section: **I-section**	Equivalent welded I-section: **EWI-section**
Rolled H-section: **H-section**	Equivalent welded H-section: **EWH-section**
Hot-finished circular hollow section: **CHS**	Equivalent cold-formed circular hollow section: **EWCHS**
Hot-finished rectangular hollow section: **RHS**	Equivalent cold-formed rectangular hollow section: **EWRHS**
Hot-finished square hollow section: **SHS**	Equivalent cold-formed square hollow section: **EWSHS**

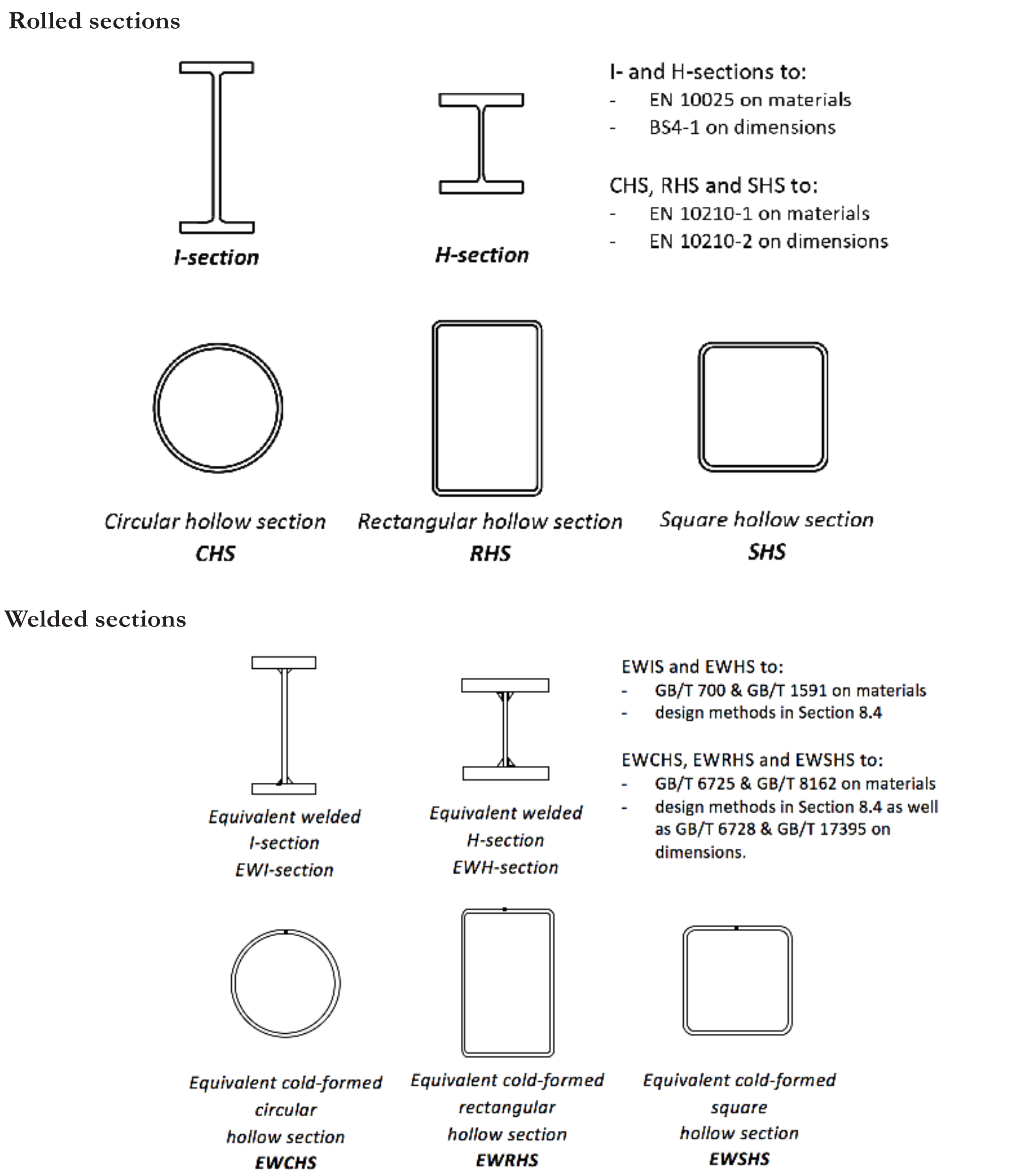


Figure 2 Cross-sections of typical rolled sections and welded sections

Table 6 Summary of design information for rolled sections

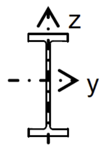
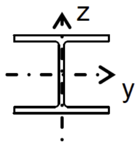
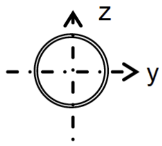
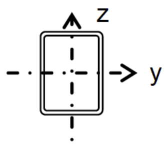
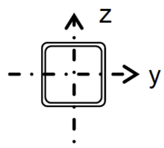
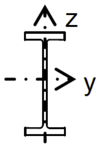
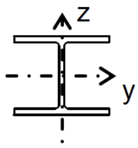
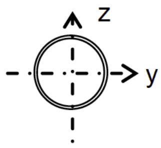
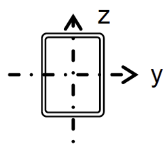
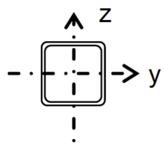
	I-section	H-section	CHS	RHS	SHS
					
Dimensions and properties	**72 sections**	**31 sections**	**55 sections**	**44 sections**	**32 sections**
Section resistances for S275 steel	√	√	√	√	√
Section resistances for S355 steel	√	√	√	√	√

Table 7 Summary of design information for welded sections

	EWI-section	EWH-section	EWCHS	EWRHS	EWSHS
					
Dimensions and properties	**72 sections**	**31 sections**	**55 sections**	**44 sections**	**32 sections**
Section resistances for Q235 steel	√	√	-	-	-
Section resistances for Q275 steel	√	√	√	√	√
Section resistances for Q345 steel	√	√	√	√	√
Section resistances for Q460 steel	√	√	√	√	√

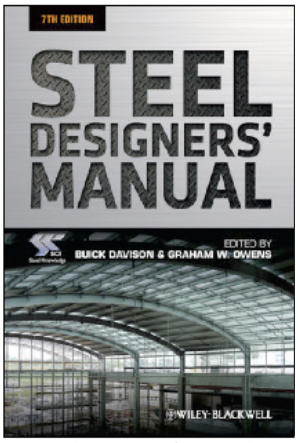
b) All the equivalent cold-formed hollow sections are manufactured with steel materials to GB/T 6725 and GB/T 8162 while their dimensions are manufactured to GB/T 6728 and GB/T 17395. All of these sections are proposed as equivalent welded sections to those rolled sections based on various structural requirements, such as compression and bending resistances.

For simplicity, Chinese steel materials are assumed to be Class 2 steel materials with a material class factor, γ_{Mc} = 1.1 as discussed in Section 3.2. Standard welding procedures are assumed to be applied effectively during their fabrication. Moreover, section resistances of all these sections with common steel grades, i.e. Q235, Q275, Q345 and Q460 steel materials, are tabulated in a systematic manner for practical design. Table 7 summarises various design information provided for the welded sections covered in the document, and a total of 27 Design Tables have been compiled covering 234 equivalent welded sections in four different steel materials.

4.3 Chinese versions of the Steel Designers' Manual 7th Edition

With the support of various industrial associations in Hong Kong and Macau SARs as well as China, in particular, the Chinese Steel Construction Society, the Chinese National Engineering Research Centre for Steel Construction, the Hong Kong Constructional Metal Structures Association and the Macau Society of Metal Structures, the latest edition of the Steel Designers' Manual had been translated into both traditional Chinese and simplified Chinese.

This classic Manual on structural steelwork design was first published in 1955 in the U.K.. Since then, the Manual had been reviewed and revised regularly over the past 56 years to incorporate latest developments and technological



Steel Designers' Manual
7th Edition
February 2012

《欧标钢结构设计手册》
第七版 简体中文版
2014 年 8 月

《鋼結構設計師手冊》
第七版 歐標 繁體中文版
2013 年 8 月

advances in steel construction in the U.K.. This Manual was regarded as one of the most widely referred structural engineering professional manuals in the U.K. as well as many European countries and Commonwealth countries in many parts of the world. All of the chapters in the 7th edition of the Manual have been comprehensively reviewed and revised to ensure they reflect current approaches and best practice, and brought in to compliance with the Structural Eurocodes. The Manual was published in February 2012 by the Steel Construction Institute in the U.K.

With the joint effort of the Chinese Steel Construction Society, the Hong Kong Constructional of Metal Structures Association and the Macau Society of Metal Structures, a total of 36 steel engineers and experts in China, Taiwan, Hong Kong and Macau worked on the translation and review work of the Manual collaboratively over a period of two years. It should be noted that the traditional Chinese version of the Manual was published in August 2013 while the simplified Chinese version was published in August 2014. These Chinese versions of the Manual will readily introduce international practice of building design and construction to Chinese engineers, in particular, on international material specifications, modern design methods as well as major considerations and requirements on overseas construction projects.

5. CONCLUSIONS

This paper describes recent research and development initiatives on effective design and construction of steel structures for the local construction industry which are positive responses to adoption of the Structural Eurocodes in Hong Kong. Both the Professional Guide on the use of equivalent steel materials and the Technical Guide on advanced structural steel design are compiled to facilitate design and construction engineers to work effectively to EN 1993-1-1 using Chinese steel materials and structural steelwork. Hence, Hong Kong design and construction engineers are encouraged to take full advantages offered by these two documents for construction projects in Hong Kong as well as neighbouring cities and countries in the Region. The Chinese versions of the Steel Designers' Manual 7th Edition will readily facilitate Chinese design and construction engineers to follow international practice on overseas construction projects.

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Part 2: Tolerances, dimensions and sectional properties. 2006.

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APPENDIX

Additional material tests required for Class E2 Steel Materials

Table A1 summarises all the additional material tests required for demonstration of conformity of a proposed equivalent steel material in order to achieve a classification as a Class E2 Steel Material.

Table A1 Additional material tests required for demonstration of conformity

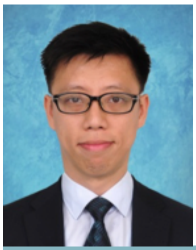
Material tests	Product forms	Parameters tested[a]	Reference Standards
Tensile Tests	Plates Sections Hollow sections Sheet piles Solid bars Strips for cold formed open sections Strips for cold formed profiled sheets Stud connectors Bolts	Yield strength Tensile strength Elongation at fracture	BS EN ISO 6892-1:2009
Charpy impact tests	Plates Sections Hollow sections	Impact energy	BS EN ISO 148-1:2010
Hardness Tests	Bolts Nuts Washers	Brinell hardness Vickers hardness Rockwell hardness	BS EN ISO 6506-1:2005 BS EN ISO 6507-1:2005 BS EN ISO 6508-1:2005
Proof load Tests	Nuts	Proof load stress	BS EN 20898-2:1994
All-weld Metal Tests	Welding consumables	Yield strength Tensile strength Elongation at fracture Impact energy	BS EN ISO 15792-1:2008
Chemical Analysis	Plates Sections Hollow sections Sheet piles Solid bars Strips for cold formed open sections Strips for cold-formed profiled sheets Bolts	Carbon content, Carbon Equivalent Value, Sulphur content, Phosphorous content, and others	BS EN ISO 14284:2002

As the inspection frequencies, the sampling sizes and the number of tests for each parameter depend on many factors, such as delivery conditions and supply, and structural applications of the steel materials as well as quality assurance requirements and relevant local regulations on the use of equivalent steel materials, it is not practical to provide general recommendations on the programme of material testing. Nevertheless, practice of quality control on the use of equivalent steel materials by regulatory authorities in a number of countries and cities in Asia is provided in Appendix C of the Professional Guide for easy reference. It is advisable to seek recommendations from these regulatory authorities for specific requirements on the additional material tests.

BIOGRAPHY

Ir Professor K. F. Chung is a Professor of the Department of Civil and Environmental Engineering at the Hong Kong Polytechnic University. He is also Founding President of the Hong Kong Constructional Metal Structures Association, and Council Member of the Institution of Structural Engineers in the U.K.. Professor Chung works on a wide range of inter-disciplinary engineering analysis and design, especially on modern steel and composite structures. His research interests include limit state analysis and performance-based design of structural steel systems, structural fire engineering and fire protection in buildings and tunnels, and design codification. In the recent years, with strong supports from the construction industry and various government departments and agents, Prof. Chung has extended his applied research interests into construction sustainability, durability of infrastructures, and corrosion protection of structural steelwork.

Ir Dr. Michael C. H. Yam is an Associate Professor of the Department of Building and Real Estate at the Hong Kong Polytechnic University. He is also Vice President of the Hong Kong Constructional Metal Structures Association. His research interests focus on the areas of strength and structural behaviour of coped steel beams, shear lag of tension members, gusset plates under compression, and application of shape memory alloys in steel connections.



Dr. H. C. Ho is a Project Fellow of the Department of Civil and Environmental Engineering at the Hong Kong Polytechnic University. He is also Technical Manager of the Hong Kong Constructional Metal Structures Association. He specialises in research and development of steel and composite structures, cold-formed metal structures, structural fire engineering, structural instability and advanced numerical modelling.

Research Papers

PREDICTING CONSTRUCTION DURATIONS AND ENHANCING CONSTRUCTION PRODUCTIVITY: A TAXONOMIC REVIEW

Daniel W.M. Chan[1,*], Albert P.C. Chan[1], Patrick T.I. Lam[1] and W.K. Lau[2]

[1] *Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong*
[2] *Faculty of Science and Technology, The Technological and Higher Education Institute of Hong Kong, Hong Kong*

In an attempt to develop statistical construction time prediction models for high-rise private building projects in Hong Kong and launch an investigation of construction time performance (CTP), a desktop taxonomic review was conducted to examine some previously developed models and to provide an overview of the current state of construction duration modelling methods. The succession of the models was captured in a number of key aspects under investigation. Of similar concern as estimating the construction time accurately, lifting construction productivity in the construction industry as a whole is targeted. Among the approaches to faster construction, only those relevant to the case in Hong Kong are reported herein. Such a review in addition to serving as a quick reference to construction time prediction and faster construction has provided valuable insights into the subjects for the on-going research study.

Keywords: Construction time performance, duration, prediction model, productivity improvement

INTRODUCTION

An accurate estimate of completion time contributes to project success (Chan and Kumaraswamy, 1995). Therefore, for years, predicting construction durations and assessing CTP have been of interest to both project managers and construction researchers (Chan, 1999). In practice, construction duration is very important to both the clients and the contractors. At the pre-contract stage it can help proper cash flow forecasting by both parties. With a realistic estimate, contractors will be assisted in cost-effective resource allocation, financial planning, profitability and efficiency of capital flow within a time limit determined in advance (Chan and Kumaraswamy, 1995). Due to increased project duration certainty, clients' own financial planning and contractor selection process will also be improved.

Being the first step, the development of a construction time prediction model that provides an optimal estimate of construction durations is essential. The estimate has to be reasonable or realistic, or delays and subsequently cost overruns will become more likely when durations are underestimated, while clients will lose valuable income when durations are overestimated. With such a time prediction model, an investigation of determinants of project duration and cross-country comparisons of CTP will become feasible and vital. The findings will help establish good practices and effective implementation strategies to speed up the construction process.

In Hong Kong, against this background, the need to develop benchmark models for construction durations is imperative. It is high time that the CTP of high-rise private building projects in Hong Kong is to be investigated, with an aim to elevate the overall competitiveness and productivity of the local construction industry. In examining the subject, current practices of project scheduling will be reviewed. Project data will be collected and analysed to establish the CTP, and the CTP will be compared against similar overseas economies. Key factors that affect project construction duration will also be identified. Good practices for enhancing the existing time performance will be recommended. As a first, this paper presents a review and discussion of published literature about construction duration modelling and means to achieve faster construction.

REVIEW METHOD

In search of previously developed construction time prediction models, only those studies that: (1) investigated the subject of construction durations; (2) have quantitative prediction model(s) developed from empirical data; and (3) were published in academic journals in English were considered. For studies which examined factors affecting construction durations without quantitative models, they were not selected for review.

To identify the desired studies, a combination of search terms "construction time" or "construction duration", "prediction" and "model" was used. An electronic search

[*]daniel.w.m.chan@polyu.edu.hk Dr. Daniel Chan

of the literature up to December 2014 was conducted, via common electronic databases of ScienceDirect#, EBSCohost#, Emerald Insight and Taylor & Francis Online. A total of 151, 120, 112 and 31 results were returned from the respective databases. The titles and abstracts of the retrieved materials were quickly reviewed. They would be selected for in-depth review and analysis if they matched the aforementioned criteria. Of these identified papers, some were duplicated and quite a number of them were found irrelevant to the subject under study. More than 25 papers were ultimately selected in the end. They were analysed against the points of interest as summarised in Table 1 and Table 2. For the purpose of this paper, only 13 selected papers with another 5^ picked by the authors were analysed and discussed.

Considering the relevance of research studies in faster construction and to narrow down the scope of search, rather than doing an extensive literature search as above, some local and overseas research studies in relation to the construction time prediction models and major factors contributing to faster project completion will be highlighted and reviewed.

#: The original number of returns from these databases was large and papers with terms "energy", "software", "tunnel" and "ship" were excluded; and
^: 2 were not available online, 2 from the American Society of Civil Engineers (ASCE) library, and 1 from another source (i.e. Le-Hoai and Lee, 2009).

Modelling Construction Durations

The Model. The first significant recorded construction duration prediction model in power regression form was developed by Bromilow (1969), with construction cost being the only independent variable, being expressed as:

$$T = KC^{B} \qquad (1)$$

where T is the duration of construction period from date of site possession to practical completion in working days, C is the final cost of building in millions of dollars adjusted to constant labour and material prices, K is a constant describing the general level of time performance of an Australian \$1 million project, and B is a constant describing how the time performance is affected by project size as measured by cost.

While the seminal Bromilow's time-cost (BTC) model gives a quick, quantitative estimation of construction duration, it failed to consider factors other than cost (Walker, 1995). Taking into account of factors in addition to or other than cost and to capture their effects on construction duration, a number of models were then developed. Ireland (1985) modelled construction time using complexity of construction form, extension of time through industrial disputes, construction planning during design and area. Walker (1995) determined workdays by construction cost, granted extension of time to actual construction period ratio, type of work, quality level of workmanship, management style and effectiveness of information technology use by the management team. Chan and Kumaraswamy (1995) used floor area, number of storeys and cost-floor area separately to model construction duration. In the study of Khosrowshahi and Kaka (1996), construction duration is given by construction cost, degree of ease of horizontal access, buildability level, type of work, structural properties of frame and floor, number of units, project start month and abnormal events occurred. Chan and Kumaraswamy (1999) adopted estimated construction cost, presence of precast façades, height of building, nature of site and type of housing scheme to model the estimated (contractual) construction duration, and they used actual construction cost, total volume of building, gross floor area to number of storeys ratio, and again type of housing scheme and presence of precast façades, to model the actual construction duration. Love *et al.* (2005) forecasted construction duration based on gross floor area and number of floor levels in a project. In the Hoffman et al. (2007)'s multifactor model, project total cost, management entity, region and design/construction agent were used to predict construction duration. Stoy et al. (2007)'s model estimated construction speed based on project size (in 1000m^2 of gross external floor area), number of winters and planning durations.

Publication Date. From the selected research studies, the earliest one was carried out in 1969 and the most recent one was conducted in 2014. Coming after the earliest one which was launched in 1985, two were done between 1990 and 1994, four were done between 1995 and 1999, two were conducted between 2000 and 2004, and six were conducted between 2005 and 2009. From this observation it is clear that modelling and predicting construction duration represents a problem of continual concern.

Country of Origin. Among the selected research studies, the CTP in Australia is the most frequently cited (six studies), followed by Hong Kong (three studies), the United Kingdom and the United States (two studies), and Germany, Malaysia, Nigeria, South Korea and Vietnam (one study). In many of these studies, the BTC model was applied and the time-cost relationship was verified with empirical data in different countries.

Sample Projects. Concerning the sample size of the selected studies, if we disregard the two research studies with an exceptionally large sample of 856 and 661 in Hoffman *et al.* (2007) and Kaka and Price (1991) respectively, on average 111 projects were examined in each study. A total of 3,175 projects were considered throughout the years. Usually the projects were further classified according to their sectors (i.e. public versus private), building type (e.g. residential and commercial), type of work (e.g. new build and renovation) and procurement method used. From the classified studies, different time prediction models were developed and their time performances were studied.

Predictive Power. Denoted by r^2 or R^2, the coefficient of determination is an accepted measure of the goodness of fit of a statistical model (Chan, 1999; Chan and Kumaraswamy, 1995). It can tell how well the model fits the population or the samples from which the model is derived, i.e. r^2 (or R^2) equals to 1 when all the observations fall on the regression line (curve) and r^2 (or R^2) equals to 0 when there is no statistical relationship between the dependent and independent variables (Chan, 1999). Sometimes, an adjusted R^2 is used as it enables the comparison of explanatory power between regression models that have different number of predictors.

Extracted from the selected research studies and reported in Table 1, the r^2 values of the BTC models ranged from 0.196 in Ogunsemi and Jagboro (2006) to 0.960 in Ng *et al.* (2001). The mean r^2 value of the models is 0.564. For other time prediction models, their r^2 (or R^2) values ranged from 0.374 in Hoffman et al. (2007) to 0.999 in Walker (1995), and they have a mean r^2 (or R^2) value of 0.731. In general the predictive power of other time prediction models is stronger than BTC models. The predictive power of the models based on their r^2 (or R^2) values is summarised below:

EFFECTIVE STRATEGIES FOR ACHIEVING FASTER CONSTRUCTION

Based on the desktop literature review, a number of ways that have perceived and proven benefits in faster construction relevant to the situation in Hong Kong were reviewed. Generally, they were grouped into technological or managerial strategies.

Technological Strategies

Improving the buildability of projects and early involvement of contractors: In Lam *et al.* (2006), they identified 63 buildability attributes and classified them to either design process or design outcome related. They then revealed in a questionnaire survey that site condition, coordination between documents/components/working sequence, standardisation and repetition, safety and ease of construction were considered to be the five most important buildability attributes with merits to reduce construction

BTC Models

Strength of Relationship	Coefficient of Determination	Research Publications
Strong	$r^2 \geq 0.7$	Chan (1999); Sousa *et al.* (2014)
Moderate	$0.4 \leq r^2 < 0.7$	Ireland (1985); Kaka and Price (1991); Chan and Kumaraswamy (1995); Chan (2001); Ng *et al.* (2001); Le-Hoai and Lee (2009); and Le-Hoai *et al.* (2009)
Weak	$r^2 < 0.4$	Ogunsemi and Jagboro (2006); and Hoffman *et al.* (2007)

Other time prediction models

Strength of Relationship	Coefficient of Determination	Research Publications
Strong	r^2 (or R^2)≥ 0.7	Walker (1995); Khosrowshahi and Kaka (1996)*; Chan and Kumaraswamy (1999); Ogunsemi and Jagboro (2006); and Stoy *et al.* (2007)
Moderate	$0.4 \leq r^2$ (or R^2) < 0.7	Love *et al.* (2005)*
Weak	r^2 (or R^2) < 0.4	Hoffman *et al.* (2007)

*Note: * Ajusted R^2, rather than r^2 (or R^2), was reported.*

Table 1 Previous research studies of construction time performance and the statistical prediction models

Study	Construction Time Prediction Model	Data and Modelling Method	Predictability
Bromilow (1969/ 1974)	$T = 313C^{0.3}$; C in 1 million Australian dollar Value at 1972 prices	370 building projects Bromilow Time-Cost Model	
Ireland (1985)	$T = 219C^{0.47}$; C in 1 million Australian dollar Value at June 1979 prices	25 high-rise commercial projects Multiple regressions	r^2 : 0.58
Kaka and Price (1991)	Civil engineering projects $T = 258.1C^{0.469}$ (Estimated) $T = 245.3C^{0.432}$ (Actual) Public building projects $T = 407.4C^{0.293}$ (Open competition) $T = 424.1C^{0.342}$ (Selected competition) $T = 367.5C^{0.272}$ (Negotiated competition) Fixed price contracts $T = 398.8C^{0.318}$ (Public buildings) $T = 274.4C^{0.212}$ (Private buildings) $T = 258.1C^{0.469}$ (Civil engineering) Adjusted price contracts $T = 486.7C^{0.205}$ (Public buildings) $T = 491.2C^{0.082}$ (Private buildings) $T = 463.3C^{0.437}$ (Civil engineering) C in 1 million pound Value at 1988 prices	661 building projects including commercial, industrial, residential and public works, and 140 road projects Bromilow Time-Cost Model	r^2 : Civil engineering projects 0.71 (Estimated) 0.71 (Actual) Public building projects 0.55 (Open competition) 0.67 (Selected competition) 0.59 (Negotiated competition) Fixed price contracts 0.58 (Public buildings) 0.24 (Private buildings) 0.71 (Civil engineering) Adjusted price contracts 0.46 (Public buildings) 0.37 (Private buildings) 0.94 (Civil engineering)
Walker (1995)	Workdays = $C^{0.481}$ x exp {(1.19eot_act) - (0.489fit) + (0.105obj_qual) – (0.125cr_people) + (0.08cm_des_com) + (0.104cm_IT_use)} where C = 1,000 Australian dollar, eot_act = ratio of extension of time granted to actual construction period, fit = 1 if project is a fit-out, obj_qual = quality of workmanship from 1 to 7 where 1 = very low and 7 = very high, cr_people = people-oriented management style from 1 to 7 where 1 = very low and 7 = very high, cm_des_com = communications management for decision making between construction and design from 1 to 7 where 1 = very low and 7 = very high, and cm_IT_use = effective use of information technologies by construction management team from 1 to 7 where 1 = very low and 7 = very high Value at January 1990 prices	33 building projects including office, industrial, education related and others Multiple regression model	r^2 : 0.9987

Chan and Kumaraswamy (1995)	Government building projects $T=182.3C^{0.277}$ (Estimated) $T=216.3C^{0.253}$ (Actual) Private building projects $T=202.6C^{0.233}$ (Estimated) $T=250.9C^{0.215}$ (Actual) Civil engineering projects $T=252.5C^{0.213}$ (Estimated) $T=291.4C^{0.205}$ (Actual) C in 1 million Hong Kong dollar	111 projects comprised of 37 government building projects, 36 private building projects, and 38 civil engineering projects Bromilow Time-Cost Model	r^2 : Government building projects 0.66 (Estimated) 0.62 (Actual) Private building projects 0.48 (Estimated) 0.42 (Actual) Civil engineering projects 0.64 (Estimated) 0.61 (Actual)
Khosrowshahi and Kaka (1996)	Model II Exponential (Duration) = Constant + $\log_e$(Cost)*Cost coef. + Horizontal access coef. + Buildability coef. + Scope coef. + Operation coef. + Frame coef. + Units*Unit coef. + Start month coef. + Abnormality coef. + Floor coef. coef. = coefficient Cost in 1 pound Value in 1985 prices	54 housing projects from different locations in the UK Multi-variate regression analysis	Adjusted R^2 : 0.927
Chan (1999)	All building projects $T = 152C^{0.29}$ All public projects $T = 166C^{0.28}$ All private projects $T = 120C^{0.34}$ C in 1 million Hong Kong dollar Value at December 1994 prices	110 projects including residential, commercial, education, industrial, hotel, health and others Bromilow Time-Cost Model	r^2 : 0.85 (All building projects) 0.91 (All public projects) 0.73 (All private projects)
Chan and Kumaraswamy (1999)	Estimated construction duration $\log_e$EST_TIME = 2.6031 + 0.0834$\log_e$EST-COST + FAÇADE (0 for w/ precast facades; 0.0497 for w/o precast facades) + 0.0024HEIGHT + NATSITE (0.2352 for level; 0.221 for built-up; 0 for sloping) + TYPESCH (-0.0453 for purchase; 0 for rental) Actual construction duration $\log_e$ACT_TIME = 3.0264 + 0.1236$\log_e$ACT-COST + TYPESCH(-0.0544 for purchase; 0 for rental) + FAÇADE (0 w/ precast facades; 0.0666 for w/o precast facades) + 1.3E-06VOLTOTAL – 0.0003GFA/NOSTOREY NATSITE = nature of site TYPESCH = type of scheme VOLTOTAL = total volume of the building (m^3) C in 1 million Hong Kong dollar Value at fourth quarter of 1996 prices	56 "Harmony" type domestic blocks Multiple linear regression	r^2 : 0.8572 (Estimated time) 0.7546 (Actual time)

Chan (2001)	$T = 269C^{0.32}$ C in 1 million Malaysian riggit Value at December 1992 prices	51 public sector including education, offices, residential, repairs and alteration, sports and others Bromilow Time-Cost Model	r^2 : 0.41
Ng *et al.* (2001)	Overall $T = 131C^{0.31}$ Public $T=129C^{0.32}$ Private $T=132C^{0.30}$ Non-industrial projects $T=152C^{0.27}$ Industrial projects $T=97C^{0.36}$ C in 1 million Australian dollar Value at March 1998 prices	93 projects Bromilow Time-Cost Model	r^2 : 0.588 (All) 0.679 (Public) 0.540 (Private) 0.538 (Non-industrial) 0.810 (Industrial)
Love *et al.* (2005)	New build ($\mu = 1$ for new build, otherwise = 0) $\log(T) = 0.656 + 0.312\log(C) + 0.221\mu$ Refurbishment/renovation ($\mu = 1$ for refurbishment/ renovation, otherwise = 0) $\log(T) = 0.697 + 0.320\log(C) - 0.145\mu$ Fit out ($\mu = 1$ for fit out, otherwise = 0) $\log(T) = 0.828 + 0.311\log(C) - 0.393\mu$ New build/refurbishment ($\mu = 1$ for new build/ refurbishment, otherwise = 0) $\log(T) = 0.57 + 0.325\log(C) + 0.113\mu$ Procurement method ($\mu = 1$ for non-traditional method, $\mu = 0$ for traditional method) $\log(T) = 0.353 + 0.345\log(C) - 0.237\mu$ Time Forecasting Model $\log(T) = 3.178 + 0.274\log(GFA) + 0.142\log(Floor)$ C in 1 million Australian dollar	161 construction projects Multiple regression using the technique of weighted least squares	Adjusted R^2: 0.589 (New build) 0.574 (Refurbishment/ renovation) 0.589 (Fit out) 0.568 (New build/ refurbishment) 0.59 (Procurement method) 0.96 (Time-Cost Forecasting Model)

Ogunsemi and Jagboro (2006)	All projects $T=63C^{0.262}$ Private projects $T=55C^{0.312}$ Public projects $T=69C^{0.255}$ For all projects $T=118.563-0.401C (C \leq 408)$ or $603.427+0.610C (C > 408)$ For private projects $T=168.895+0.491C (C \leq 557)$ or $709.66+0.884C (C > 557)$ For public projects $T=98.010+0.357C (C \leq 353)$ or $567.967+0.283C (C > 353)$ C in 1 million Nigerian naira Value at 2000 prices	87 building projects including residential, commercial, educational and others Bromilow Time-Cost Model and piecewise linear regression with breakpoint	r^2: Bromilow Time-Cost Model 0.205 (All projects) 0.196 (Private projects) 0.322 (Public projects) Piecewise linear regression with breakpoint 0.7656 (All projects) 0.7762 (Private projects) 0.8306 (Public projects)
Hoffman *et al.* (2007)	All projects $T=26.8C^{0.202}$ MAJCOM $T=24.3C^{0.215}$(AFMC) T=30.9C0.191(All others) COE regions $T=41.3C^{0.170}$(NW, Pacific Ocean) $T=22.6C^{0.216}$(All others) D/C agent $T=24.3C^{0.213}$(NAVFAC) $T=32.1C^{0.190}$(COE) $T=22.0C^{0.210}$(In-house) Temperature $T=27.4\ C^{0.204}$(High) $T=20.9C^{0.219}$(Medium) $T=32.1C^{0.187}$(Low) C in 1 million US dollar Value at 2004 prices MAJCOM = Major Command AFMC = Air Force Materiel Command COE = Corps of Engineers NAVFAC = Naval Facilities Engineering Command ACC = Air Combat Command AETC = Air Education and Training Command AFSOC = Air Force Special Operations Command D/C = design/construction Multifactor model $y=3.44+0.198x_1-0.059x_2-0.070x_3-0.222x_4-0.193x_5-0.0146x_6$ where y=project construction duration (in days), x_1=project total cost (in \$), remaining x_i values represent dummy variable for ACC, AETC, AFSOC, NW COE region and in-house D/C agent, respectively	856 military facility projects Bromilow Time-Cost Model and multiple linear regression	r^2: All projects 0.337 MAJCOM 0.326 (AFMC) 0.323 (All others) COE regions 0.276 (NW, Pacific Ocean) 0.374 (All others) D/C agent 0.328 (NAVFAC) 0.291 (COE) 0.448 (In-house) Temperature 0.349 (High) 0.344 (Medium) 0.335 (Low) Multifactor model 0.374

Stoy *et al.* (2007)	Model 1 $\ln(y)=6.482+0.968\ln(x_1)-0.361x_2-0.469\ln(x_3)$ where y=construction speed (m^2 gross external floor area/month), x_1=project size (in $1000m^2$ gross external floor area), x_2=no. of winters and x_3=planning duration (in months)	216 projects Weighted least squares regression	r^2 : 0.629 (Model 1) 0.915 (Model 2, log-log transformation)
Le-Hoai and Lee (2009)	All projects $T=341C^{0.175}$(All) Sector $T=359C^{0.166}$(Public) $T=220C^{0.267}$(Private) Tender method $T=366C^{0.156}$(Open) $T=238C^{0.251}$(Negotiated) Project type $T=369C^{0.158}$(Residential) $T=225C^{0.268}$(Commercial) $T=386C^{0.124}$(Others) C in 1 billion South Korean won Value at 2000 prices	34 building projects including residential, commercial and others Bromilow Time-Cost Model and different regression models	r^2 : Sector 0.657(All) 0.619(Public) 0.707(Private) Tender method: 0.553(Open) 0.809(Negoitated) Project type: 0.766(Residential) 0.934(Commercial) 0.246(Others)
Le-Hoai *et al.* (2009)	All cases $T=93.6C^{0.338}$ Public sector projects $T=98.1C^{0.343}$ Private sector projects $T=87.2C^{0.348}$ C in 1 billion Vietnamese dong Value at 2000 prices	77 building projects including residential, commercial, educational and others Bromilow Time-Cost Model and different regression models	r^2 : 0.403 (All cases) 0.436 (Public sector projects) 0.377 (Private sector projects)
Sousa *et al.* (2014)	Using weighted least-squares techniques Sanitation projects $\log(T)=0.4695\log(EC)+0.7003$ Water projects $\log(T)=0.5265\log(EC)+0.5318$ Sewer projects $\log(T)=0.4108\log(EC)+0.8879$ Using least-squares techniques Sanitation projects $\log(T)=0.4519\log(EC)+0.7443$ Water projects $\log(T)=0.4763\log(EC)+0.6585$ Sewer projects $\log(T)=0.4357\log(EC)+0.8259$ EC: estimate costs C in 1 thousand US dollar Value at 2002 prices	180 sanitation (i.e. water and sewer) projects in Chicago Linear regressions performed by least-squares and weighted least-squares techniques	r^2 : Using weighted least-squares techniques 0.7251 (Sanitation) 0.7547 (Water) 0.7301 (Sewer) Using least-squares techniques 0.6841 (Sanitation) 0.6778 (Water) 0.7255 (Sewer)

Table 2 Key factors or parameters included in construction time prediction models

Study	Factors			
	Project-scope	**Project complexity**	**Project Environment**	**Management Attributes**
Bromilow (1969/1974)	Construction cost			
Ireland (1985)	Construction cost			
Kaka and Price (1991)	Construction cost; Building type; Project sector; Procurement system			
Walker (1995)	Construction cost; Ratio of extension of time to actual construction period; Nature of project			Management style; Communications management for decision making; Effective use of information technologies
Chan and Kumaraswamy (1995)	Construction cost			
Khosrowshahi and Kaka (1996)	Construction cost; Scope of construction; Nature of project; Type of frame; Number of units; Materials of slab construction	Horizontal access; Buildability	Starting month	Abnormality in the following areas: access, communication, mistake, delays, stoppages, speed up, resource, cost limit, occupied, variations, transport, time limit, unknown, and others
Chan (1999)	Construction cost; Project sector			
Chan and Kumaraswamy (1999)	Construction cost; Building height; Gross floor area; Number of floors; Total volume of building	Presence of precast facades; Nature of site	Type of housing scheme	
Chan (2001)	Construction cost			
Ng *et al.* (2001)	Construction cost Project sector Building type			
Love *et al.* (2005)	Construction cost; Nature of project; Procurement system; Gross floor area; Number of floors;			
Ogunsemi and Jagboro (2006)	Construction cost; Project sector			
Hoffman *et al.* (2007)	Construction cost	Client	Region; Temperature	Agent of design/ construction
Stoy *et al.* (2007)	Project size in 1000m^2 gross external floor area		Number of winters	Planning duration in months
Le-Hoai and Lee (2009)	Construction cost; Project type; Procurement system; Project sector			
Le-Hoai *et al.* (2009)	Construction cost; Project sector			
Sousa *et al.* (2014)	Construction cost; Project type			

time. Singapore, for example, has proactively taken measures to improve buildability, including the carrying out of official buildability and constructability assessments under the related legislation.

Standardisation, modularisation and repetition in building design and construction details: Repetition of similar precast elements at every floor, repetition of similar design across building blocks, standard modular design and modular design were perceived by local construction professionals as the most important and most frequently used design factors when using prefabrication to reap fruit in faster construction (Jaillon and Poon, 2010).

Increasing the adoption of prefabrication and precast components: In Jaillon and Poon (2010)'s survey, construction professionals were neutral to using prefabrication for shorter construction time and improved productivity. Opposite to such views, findings from case studies suggested that prefabrication not only saved time but also design and construction costs. Similarly in Chan and Chan (2002)'s study of design and construction innovations in public housing construction, they found that prefabricated construction shortened the time for superstructure erection significantly. In Chan and Kumaraswamy (1999), they found statistically that using precast facades can shorten construction time. The subsequent mandatory use of precast concrete façade panels and semi-precast concrete floor slabs in all public housing constructions and wider use of prefabrication in other building components to accelerate floor cycle time were recommended by Chan and Kumaraswamy (2002) to reduce overall construction duration.

Using more efficient concrete pumps for concreting: According to Chan and Kumaraswamy (1995)'s field observations, concrete placing by pumping was more productive than crane and skip leading to a shorter floor cycle time. Site data reported in Wang and Anson (1999) concurred that concrete placing by pumping method was the most productive method of concreting above ground level. From the studies, it is evidenced that the use of concrete pumps with a higher pump rate can shorten construction time.

Other strategies: Chan and Kumararswamy (2002) also recommended some other strategies to achieve faster construction based on their surveys with industry experts:

(i) maximise mechanisation in the construction process; (ii) construction sequence should be efficient and simple; (iii) increase the number of tower cranes and sets of large panel steel formwork used in a project; (iv) use jack-up working platforms that carry proprietary wall forms themselves to save crane time for transporting the formwork around the site; and (iv) encourage symmetry in block layout for contractors to adopt innovative construction methods or system formworks. Besides, brought up again in Chan and Chan (2004) was using a CTP index for benchmarking expected duration against trend-line for above and below trend performance analysis:

Construction time performance (CTP) index
= (Predicted duration / Actual duration) x 100% (2)

Managerial Strategies

According to Kumaraswamy and Chan (1999), Chan and Kumaraswamy (2002), and Chan and Chan (2002), a series of research studies were conducted to investigate the managerial approaches to facilitate faster construction in Hong Kong. The managerial approaches revealed include:

Ensure continuous workflow for minimising floor cycle time: Maintaining continuous workflow especially for critical resources such as tower crane, large panel formwork, pumped concrete, etc. is essential to minimise floor cycle time so as to shorten overall construction duration.

Ensure co-ordinated workflow among all trades: Ensuring a coordinated workflow among all trades by more effective site management and supervision, and equally important is to maintain close liaison with all contracting parties.

Innovations in procurement method: Contemplate on project basis the suitability of adopting alternative (innovative) procurement methods for reduced construction durations, e.g. using fast-track, design-and-build and negotiated contracts, adopting a partnering approach via relational or collaborative contracting, and more recently, the introduction of target cost contracts (e.g. Chan *et al*., 2010) and the New Engineering Contracts (NECs) (e.g. Chan *et al*., 2014).

Management for better communications and decision making: For better communications, the development of appropriate overall organisational structures and information communication network systems that link all project teams throughout the project processes; defines clearly the roles and responsibilities of each party participating in the project, and increase coordination of design and construction teams at the design-construction interface are recommended. For better communications and faster information flows to happen, training programmes and formal education in integrated management information systems and advanced information processing technology should be provided to industrial practitioners.

For better decision making, not only should appointed decision-makers be clearly identified and mobilised but also they should be provided with decision aids.

Application of building information modelling (BIM) tools: BIM tools have received increasing attention and wider application in the construction industry to improve the production performance over the past decade (Froese, 2010). Cao *et al*. (2014) advocated that BIM can be applied to clash detection of various activities during the design stage by checking any possible conflicts amongst building systems prior to construction, as well as simulating master programmes and construction sequences. Hanna *et al*. (2014) also asserted that the most significant level of value generated by the use of BIM on daily project activities is to identify any design flaws or mitigate any conflicting coordinations via the clash detection programmes before the commencement of work at site level. Therefore, a wider application of BIM during the design phase should be able to achieve faster construction and higher productivity by avoiding potential field clashes or conflicts and more prompt co-ordinations of different site activities during construction as a whole.

CONCLUSIONS

Neither over-estimate nor under-estimate of construction duration is desirable from a commercial and management perspective as either can adversely affect commercial arrangements previously made. Construction time prediction models giving reasonable or realistic estimates are much in demand for that reason. In this paper published works to-date in construction duration modelling and approaches to achieve faster construction were reviewed. Placing particular concerns about the situation in Hong Kong, the review paved the way for an on-going research study to investigate the CTP of high-rise private building projects in Hong Kong on the one hand and to elevate the overall competitiveness and productivity of the local construction industry on the other.

By examining 18 published papers an overview of the current state of construction time prediction was provided. Founding on the BTC model, project-scope, project complexity and project environment related factors and management attributes are used in addition to cost to predict construction durations. Around 110 projects are considered in each study to develop different time prediction models. The predictive power of the models, as their coefficient of determination r^2 (or R^2) values reflected, varies a lot. Construction cost being the most commonly used predictor of time, if converted to a common currency and base year price, gives clues to construction productivity of countries over time making cross-country comparisons of CTP possible.

Reported in the previous studies, effective strategies for enabling faster construction in Hong Kong are either technological or managerial in nature. From the technological perspective, shorter construction duration will be resulted from improvements in buildability, standardisation, modularisation and repetition of building designs, increasing use of prefabrication and precast components, and putting to use more efficient construction methods. From the managerial aspect to save construction time, coordinating and maintaining continuous workflow, use of innovative procurement methods, and managing for better communication and decision making, together with introducing BIM tools, are recommended for reaping the potential benefits.

ACKNOWLEDGEMENTS

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BIOGRAPHY

Cr Dr. Daniel W.M. Chan, is an Associate Professor in Construction Project Management and the Programme Award Co-ordinator for MSc/PgD in Construction and Real Estate at the Department of Building and Real Estate of The Hong Kong Polytechnic University. He is a Chartered Building Engineer and Registered Construction Manager by profession. His current research interests include construction time performance, relational and collaborative contracting, target cost contracting, New Engineering Contract (NEC), and construction safety management. He has co-authored 12 research monographs, 1 scholarly textbook, 2 book chapters, 85 journal articles and 103 conference papers so far. He was also the winner of the Departmental Research Publication Awards at "Associate Professor" Level for three consecutive academic years.

Sr Dr. Patrick T.I. Lam, is an Associate Professor in Construction Economics and Project Financing and the Programme Award Co-ordinator for MSc/PgD in Project Management at the Department of Building and Real Estate of The Hong Kong Polytechnic University. He is a Registered Professional Surveyor and Registered Professional Engineer by profession. His current research interests include procurement systems, project financing, PPP, business models, construction contracts and specifications, quality and buildability issues, and carbon trading. Dr Lam had practised for 10 years in multi-disciplinary design office, consultant quantity surveyors and contractor/developer both in Hong Kong and Singapore. Whilst teaching, Dr Lam is active in research and consultancy projects. The teaching team (MSc/PgD in Project Management) which he leads has won outstanding Academic Programme Development Awards at both the departmental and faculty levels in 2009/2010.

Ir Prof. Albert P.C. Chan, is a Chair Professor of Construction Engineering and Management and the Head of the Department of Building and Real Estate of The Hong Kong Polytechnic University. His research and teaching interests cover project management and project success, construction procurement and relational contracting, construction management and economics, construction health and safety, and construction industry development. Apart from teaching and research, Prof Chan has been commissioned by a number of organizations to provide consultancy services in project management and construction health and safety.

Dr. Elvis W.K. Lau, is currently a Lecturer at the Faculty of Science and Technology of The Technological and Higher Education Institute of Hong Kong (THEi). He earned a bachelor's degree in surveying in 2008 and a PhD degree in Facilities Management in 2014 from HKU. Other than investigating the construction time performance of high-rise private building projects in this CIC funded research project, his research interests also cover sustainable buildings, open buildings, facilities management and construction management.

SIMPLIFIED SEISMIC ASSESSMENT OF RC BUILDINGS IN HONG KONG UNDER OCCASIONAL EARTHQUAKE ACTION

Ray K.L. Su[1,*], Tim O. Tang[1], C.L. Lee[1] and Hing-ho Tsang[2]

[1] *Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong*
[2]*Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia*

Seismic design of buildings will be implemented in Hong Kong (HK) in the near future. A versatile Timoshenko beam model integrated with modal response spectrum analysis is proposed for assessing the seismic performance of low-rise reinforced concrete (RC) frames and high-rise RC wall buildings with or without transfer structures. Occasional earthquake design spectra with a return period of 475 years for different site conditions in HK have been constructed. A set of design charts correlating the seismic demands (e.g. response spectral acceleration, shear area ratio, roof drift ratio and interstorey drift ratio) to the translational fundamental period of buildings has been developed as a convenient preliminary seismic checking and assessment tool. This generalised tool can provide a rapid checking of the seismic performance of an immense volume of existing and new buildings and can easily be implemented by engineers without any prior knowledge of seismic design.

Keywords: Interstorey drift ratio, modal response spectrum analysis, occasional earthquake, Timoshenko beam model, transfer structure.

INTRODUCTION

Despite the fact that Hong Kong (HK) is located in a region of low-to-moderate seismicity, no seismic code has been enforced. Introducing a new seismic code requires re-examination of the seismic resistance of existing buildings accompanied by suitable retrofitting measures. The potential onerous workloads in designing skyscrapers with complex structural forms and unforeseeable consequences hinder stakeholders from giving their consent to seismic code development. Hence, the development of convenient simplified techniques without constructing a fully detailed frame model (Chopra, 2007) for rapidly assessing the seismic performance of an immense volume of existing as well as new buildings is required.

The use of a simple Timoshenko beam (TB) for modelling the dynamic behaviour of a real building has been validated by Boutin *et al.* (2005). Two regular low-rise reinforced concrete (RC) buildings ranging from 22 m to 43 m high were investigated. By calibrating the first and second translational frequencies of the buildings from ambient vibration tests (AVT), the uniform TB model was capable of simulating the mode shapes and higher modal frequencies. Cheng and Heaton (2013) further introduced a soil spring at the base of a prismatic TB model and successfully reproduced the first and second mode shapes of a nine-storey RC frame building with a core wall. A similar study was conducted by Kohler *et al.* (2013) on a prismatic 12-storey RC shear wall building with one level basement. The aforementioned findings prove the versatility of using a prismatic TB model in estimating the dynamic behaviour of a real building.

Based on the translational vibration periods of local buildings identified from AVTs, and TB models calibrated in the previous studies (Tang and Su, 2014b), this paper aims to assess the seismic performance of typical local high-rise RC wall and low-rise RC frame buildings. The modal response spectrum analyses (MRSA) considering the first four modes of the calibrated TB models are conducted by using the proposed occasional earthquake design spectra with a return period (RP) of 475 years for typical rock and soil sites in HK. Finally, a set of design charts for logging response spectral acceleration (RSA), shear area ratio, roof drift ratio (RDR) and interstorey drift ratio (IDR) is constructed, by which preliminary seismic assessments of buildings can be easily and rapidly performed once the fundamental translational structural periods are determined.

TIMOSHENKO BEAM MODEL FOR SIMULATING RC BUILDINGS

Timoshenko Beam Theory (TBT)

Due to the length limitation of this paper, only the relevant parameters (e.g. frequency ratio and shear-to-flexural stiffness ratio) of the two-dimensional fixed-free TB model (Figure 1) will be presented. Detailed derivation and verification of a non-uniform TB model can be found in Tang and Su (2014b).

*klsu@hku.hk Dr. Ray Su

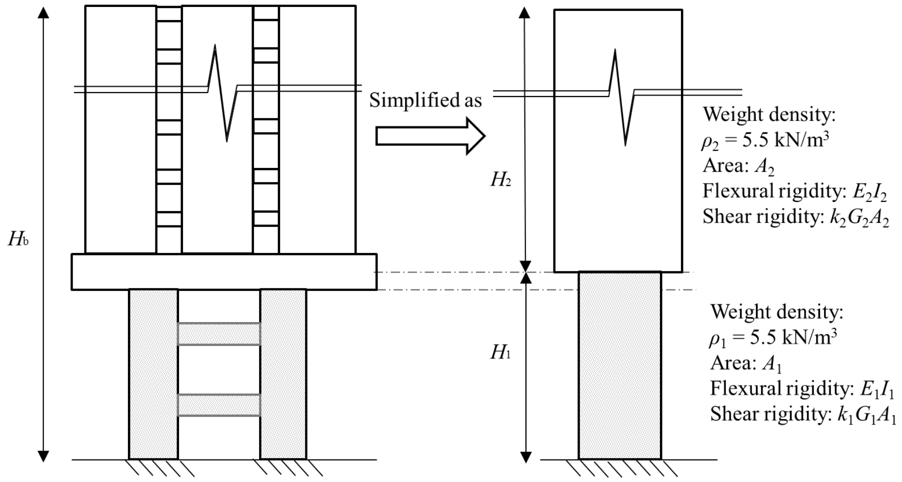


Figure 1 Non-uniform Timoshenko Beam Model and Notations of Properties

The shear-to-flexural stiffness ratios (r_{sf}) of a uniform TB can be defined as (Boutin *et al.*, 2005; Cheng and Heaton, 2013):

$$r_{sf} = \frac{\frac{kGA}{H_b}}{\frac{EI}{H_b^3}} = \frac{GH_b^2}{E}\frac{kA}{I} \qquad (1a)$$

$$r_{sf} = \frac{GH_b^2}{E}\frac{8}{D^2}$$

(for rectangular cross-section with k=2/3) (1b)

in which G and I are the equivalent shear modulus and moment of inertia of the TB model, k is the shear factor adopted to adjust for different cross-sectional shapes, A is the plane area of the building, D is the span of the plane area along the vibrating direction, E is the equivalent Young's modulus and H_b is the total height of the building (H_b / D is the aspect ratio).

For r_{sf} approaching $+\infty$, the model degenerates into an Euler-Bernoulli beam with flexural action only (i.e. without shear deformation) and the frequency ratios for the second to fourth modes (with respect to the first mode) are close to 6.3, 17.4 and 34.0, respectively; whereas r_{sf} approaching 0 refers to a simple shear beam and the corresponding frequency ratios diminish to 3, 5 and 7. Thus, the r_{sf} factor for the TB model can easily be calibrated by matching the first two translational modal frequencies if they can be obtained from AVTs or numerical modelling.

Dynamic Behaviours of RC Buildings

A database comprising in-situ dynamic tests of buildings has been compiled by Tang and Su (2014b) through a literature review and previous in-situ tests in HK by Su *et al.* (2003). These data consist of 75 buildings with different structural forms including simple shear walls, moment frames or infilled frame buildings and high-rise coupled shear walls with core walls, tube-in-tube or outrigger belt truss. Some of these are constructed above RC transfer plates or frames.

Of the 41 local medium-to-high-rise buildings with a mean height > 100 m, 21 buildings exhibit an r_{sf} ranging from 0.4 (shear-mode dominant) to 40 (flexural-mode dominant) with a median of around 10 (Tang and Su, 2014b). There are six local low-rise buildings having five to nine storeys (H_b < 40 m), and only one of these has an identified second mode frequency ratio corresponding to r_{sf} = 0.2 which exhibits a shear-mode behaviour.

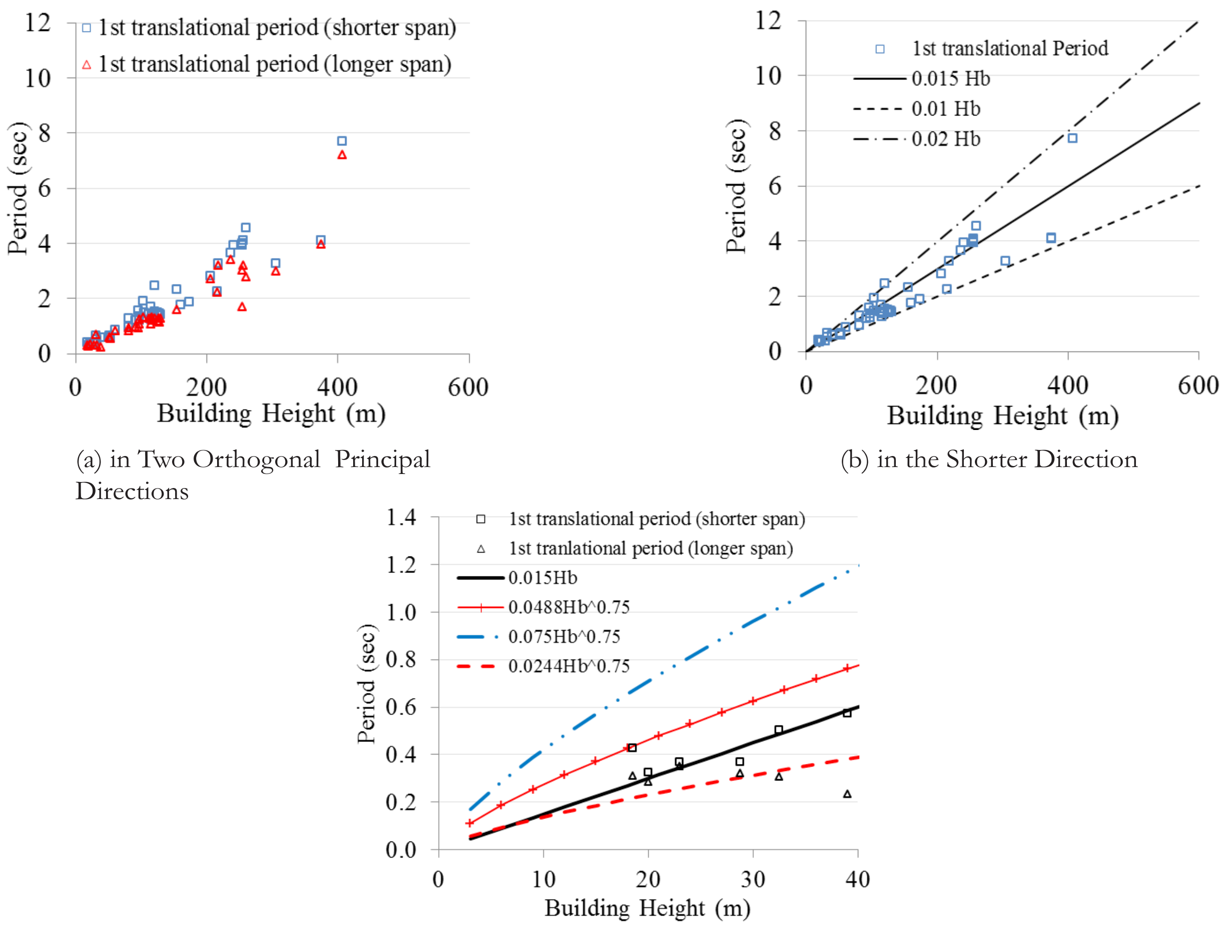
Figure 2 shows the measured translational fundamental periods in conjunction with building height. A simple period-height equation for the intact structures in HK can be deduced from small amplitude vibration tests as:

$$T_{wall,i} = 0.015H_b \text{ for RC wall buildings} \qquad (2)$$

in which the subscript i denotes the intact period obtained from small amplitude vibration data.

From Figure (2b), the coefficients of the lower-bound and upper-bound period-height equations can be reasonably assumed as 0.01 and 0.02, respectively.

For local low-rise RC frame buildings (H_b ≤ 40 m) with infills, either Equation (2) or the period-height Equation (3) in accordance with FEMA 450 (BSSC, 2004) may be adopted. For pure RC frame buildings, since there is a paucity of local dynamic test results, it is recommended that EC8 be followed (BSI, 2004a):



(a) in Two Orthogonal Principal Directions

(b) in the Shorter Direction

(c) for Low-rise Buildings Only

Figure 2 Comparisons of First Translational Periods with Building Height

$T_{infilledframe,i} = 0.0488H_b^{(3/4)}$ for RC frame buildings with infill walls (FEMA 450) (3)

$T_{frame,i} = 0.075H_b^{(3/4)}$ for pure RC frame buildings with $H_b \leq 40$ m (EC8) (4)

Figure (2c) compares the periods estimated by Equations (2) to (4) for low-rise buildings, and the measured fundamental translational periods of local buildings (with infilled walls) are also provided for comparison. Equation (2) generally gives a closer prediction whereas Equation (3) forms an upper-bound estimate to the experimental results. Half of Equation (3) (i.e. $0.0244H_b^{(3/4)}$), or $0.01H_b$, is regarded as the lower-bound estimate for low-rise infilled frame buildings.

Under seismic action, structural members may crack and a stiffness reduction factor of 0.5 (EC8, BSI, 2004a; ACI318-11, 2011) is further considered for the cracked sectional properties, whereby a period lengthening factor β_i is introduced:

$$\beta_i = \frac{1}{\sqrt{0.5}} = 1.414 \quad (5)$$

The identified frequency ratios with r_{sf} are shown in Figure (3a). Good agreement between the measured and predicted results has been achieved (Tang and Su, 2014b). Amongst the identified r_{sf}, which ranges from 0.1 to 40, the median value of $r_{sf} = 10$ is adopted for simulating the combined shear and flexural modes for medium-to-high-rise shear wall buildings with 14 to 40 storeys; whereas $r_{sf} = 0.1$ is adopted for low-rise frame buildings with two to ten storeys. Although the frequency ratio for a constant r_{sf} may vary with the aspect ratio ($=H_b/D$), the changes are modest within a certain range of r_{sf}, particularly for the lower modes. Figure (3b) compares the frequency ratios for prismatic buildings with 16 and 30 storeys predicted by TBT. The TBT yields higher frequency ratios for the 30-storey TB model with higher r_{sf} ; however, such discrepancy diminishes rapidly when $r_{sf} < 15$.

DESIGN EARTHQUAKE MODEL FOR HONG KONG

Rock Sites

The recommended design spectrum (DS) for rock sites (Su *et al.*, 2014a; Su *et al.*, 2014b; Tsang, 2006) for occasional earthquake actions with a RP of 475 years (or 10% probability of exceedance in 50 years) in HK can be expressed using Equation (6) in the format of response spectral displacement (RSD) with 5% damping versus natural period of structure (T).

$$
\begin{aligned}
&T \leq 0.23 &&: RSD(mm) = 0.28 \times (T/2\pi)^2 \times 9810 \\
&0.23 < T \leq 1.0 &&: RSD(mm) = 16 \times T \qquad (6)\\
&1.0 < T \leq 5.0 &&: RSD(mm) = 16 + 7 \times (T\text{-}1)
\end{aligned}
$$

The compatible response spectral velocity (RSV) and acceleration (RSA) can be conveniently obtained by direct transformation from the RSD, respectively, as:

$$RSV\,(mm/s) = RSD\,(mm) \times \left(\frac{2\pi}{T}\right) \qquad (7)$$

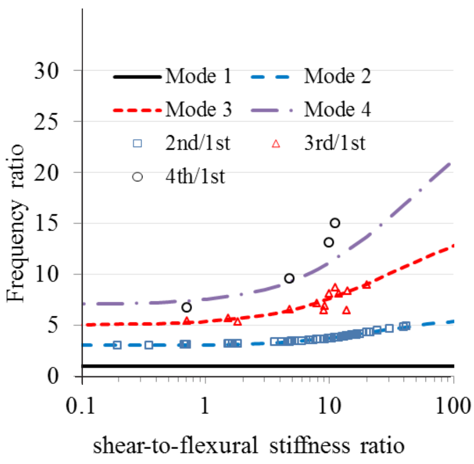
$$RSA\,(g) = RSD\,(mm) \times \left(\frac{2\pi}{T}\right)^2 / 9810 \qquad (8)$$

The rock DS for HK in RSD and RSA formats with a RP of 475 years and the confident period limit of 5.0 s are shown in Figure 4.

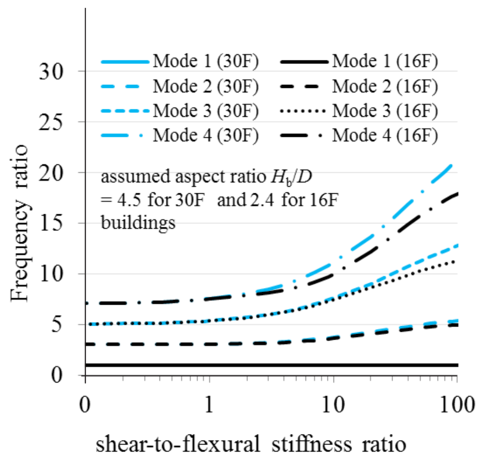
Soil Sites

Soil column profiles from 16 different site locations (Figure 5) in HK have been collected in order to construct the site-specific response spectra using STRATA (Kottke *et al.*, 2013). Site response analyses have been performed using a suite of simulated acceleration time histories that are compatible with the design occasional earthquake actions. The average spectral ratios (SR) for each site can be obtained. The SR is defined as the ratio between the *RSD* of the soil surface and that of the bedrock. By multiplying the rock DS (*RSA* or *RSD*) with the SR, the site-specific response spectra can be constructed, which have been presented in acceleration-displacement response spectrum (ADRS) format in Figure 6. Moreover, the enveloped earthquake response spectrum in the tripartite format for each soil type is also shown in Figure 6.

Earthquake Design Spectra for Typical Site Conditions in HK

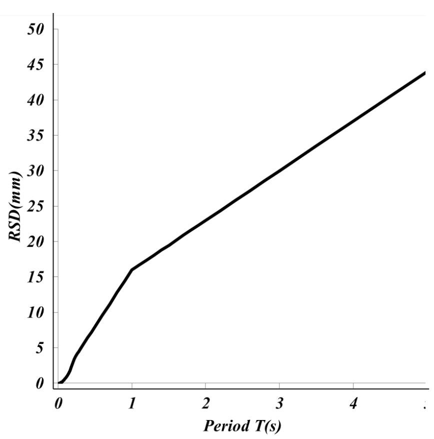


(a) Measured (Data Points) and Predicted Results from a Uniform 30-Storey TB



(b) Predicted Results for 16-storey and 30-storey Buildings Based on Uniform TBs (Tang and Su, 2014b)

Figure 3 Comparisons of Frequency Ratios with r_{sf} (Tang and Su, 2014b)



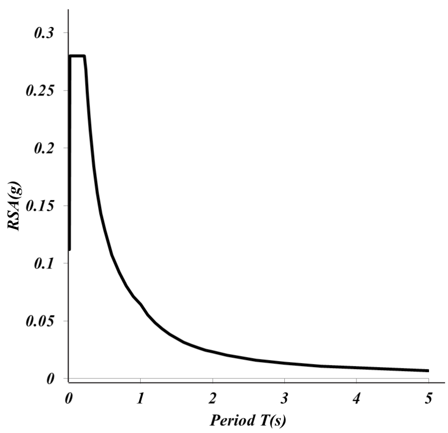


Figure 4 Rock Design Spectra for HK Presented in RSD and RSA Formats

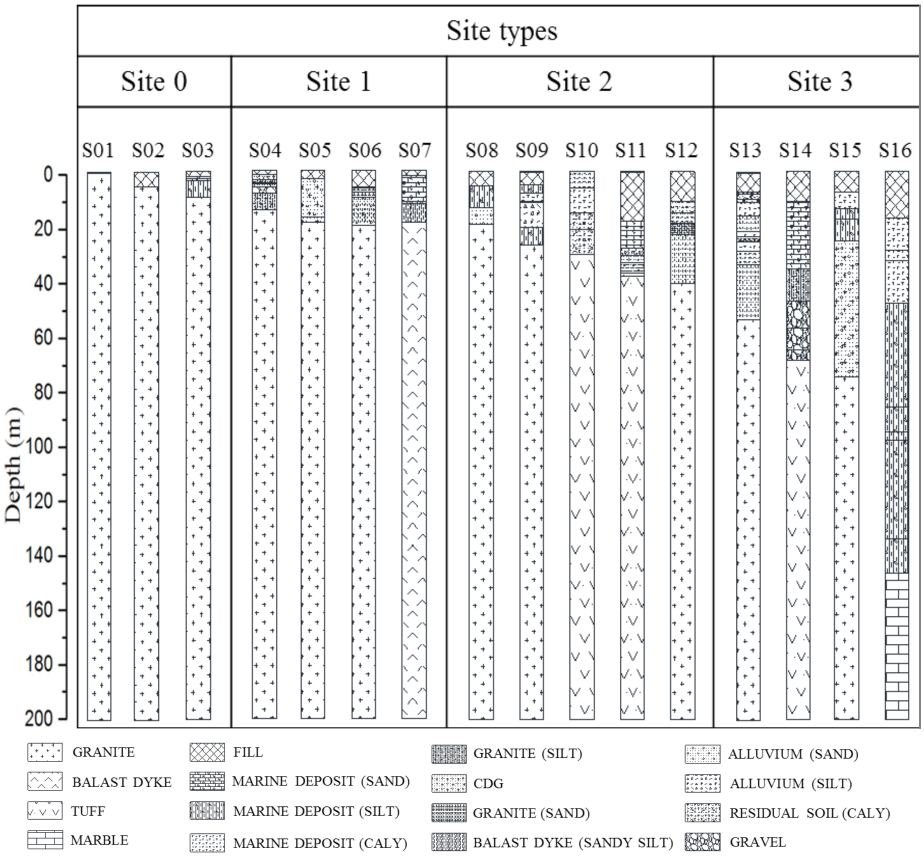


Figure 5 Borehole Records of the 16 Selected Sites in HK

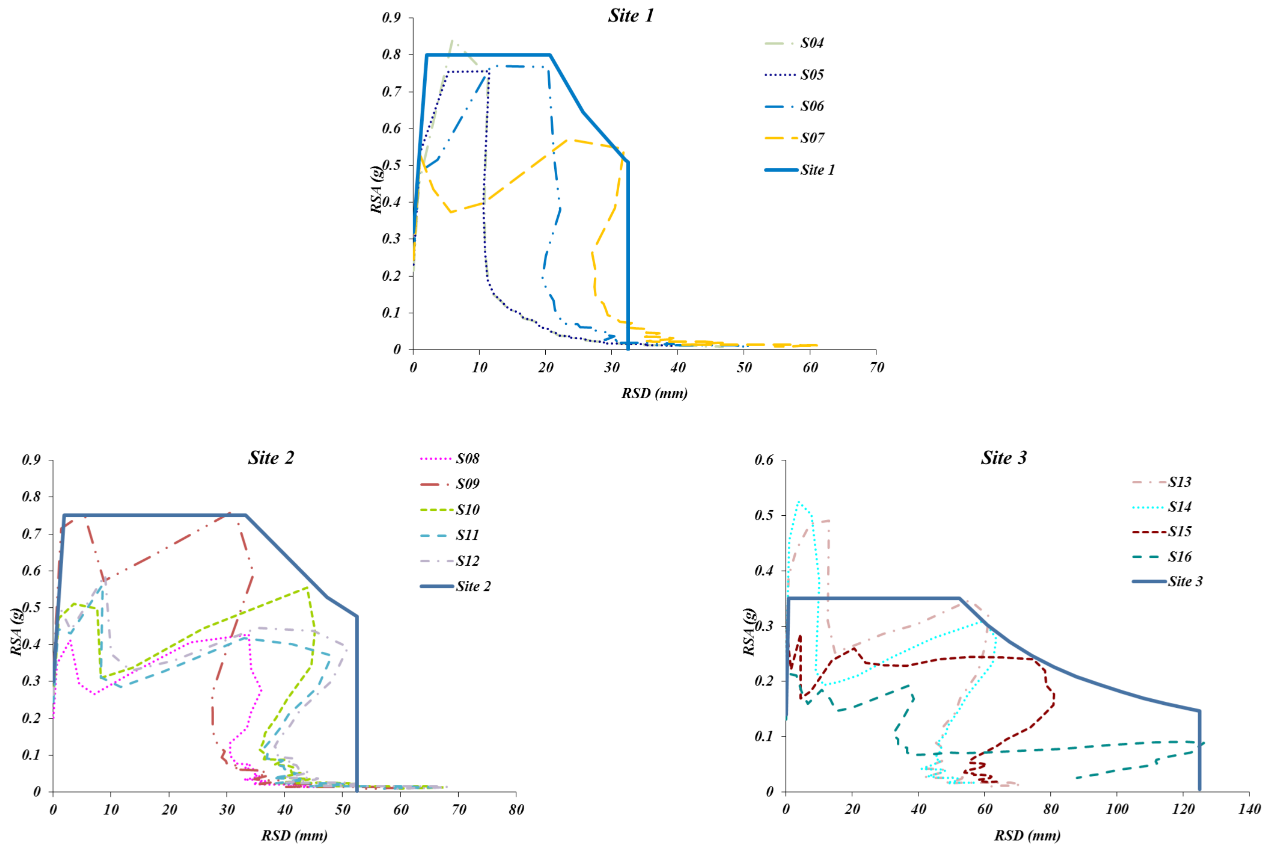


Figure 6 Site-specific Response Spectra and Proposed Earthquake Design Spectra for the Three Typical Soil Site Conditions in HK

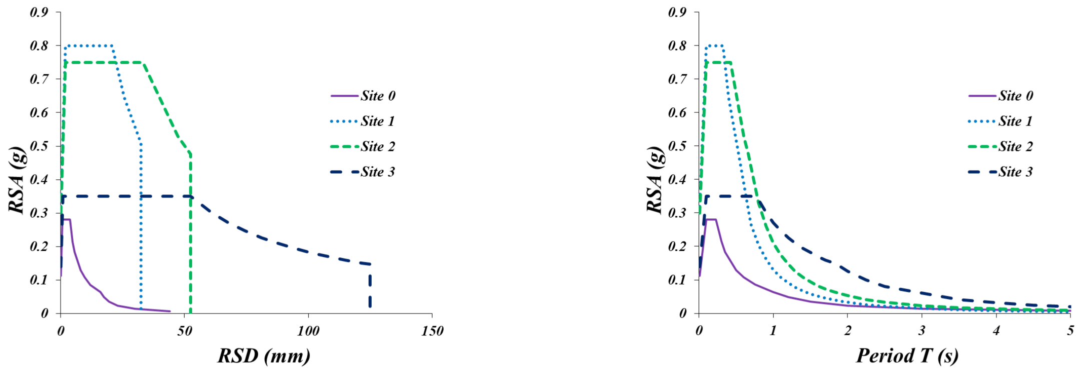


Figure 7 Proposed Four Earthquake Design Spectra for HK in ADRS and RSA Formats

The 16 site-specific response spectra can be grouped into four types (namely, Site 0, Site 1, Site 2 and Site 3). It is noted that a site with relatively thin and/or stiff soil layers and with the initial natural period $T_i \leq 0.15$s (i.e. S01 to S03) can be classified as a rock site (i.e. Site 0), and the rock DS model can be adopted.

The four occasional earthquake DS for HK are shown in Figure 7 in ADRS and *RSA* formats. This set of DS for the four typical site conditions could be a convenient engineering design tool. If the translational fundamental vibration periods of buildings are known, then the seismic force and displacement demands under different types of site conditions can be estimated.

SEISMIC DEMAND ASSESSMENT USING THE TB MODEL

RSA and Shear Area Ratio Demands

MRSA has been conducted on the calibrated TB model. The responses of the first four translational vibration modes have been combined using the square-root-of-the-sum-of-squares (SRSS) approach. The buildings with a constant storey height of 3 m, mass density of 5.5 kN/m^3 and a span (D) of plane area of 20 m are assumed to possess uniform lateral stiffness along the height of the TB models. The accumulated participating mass ratio has reached 90% as stipulated in EC8 (BSI, 2004a). Due to the length limitation of this paper, only results with significant implications (i.e. buildings subjected to Site 2 or Site 3 design spectra in this study) are presented.

Figure (8a) shows the RSA with the normalised first

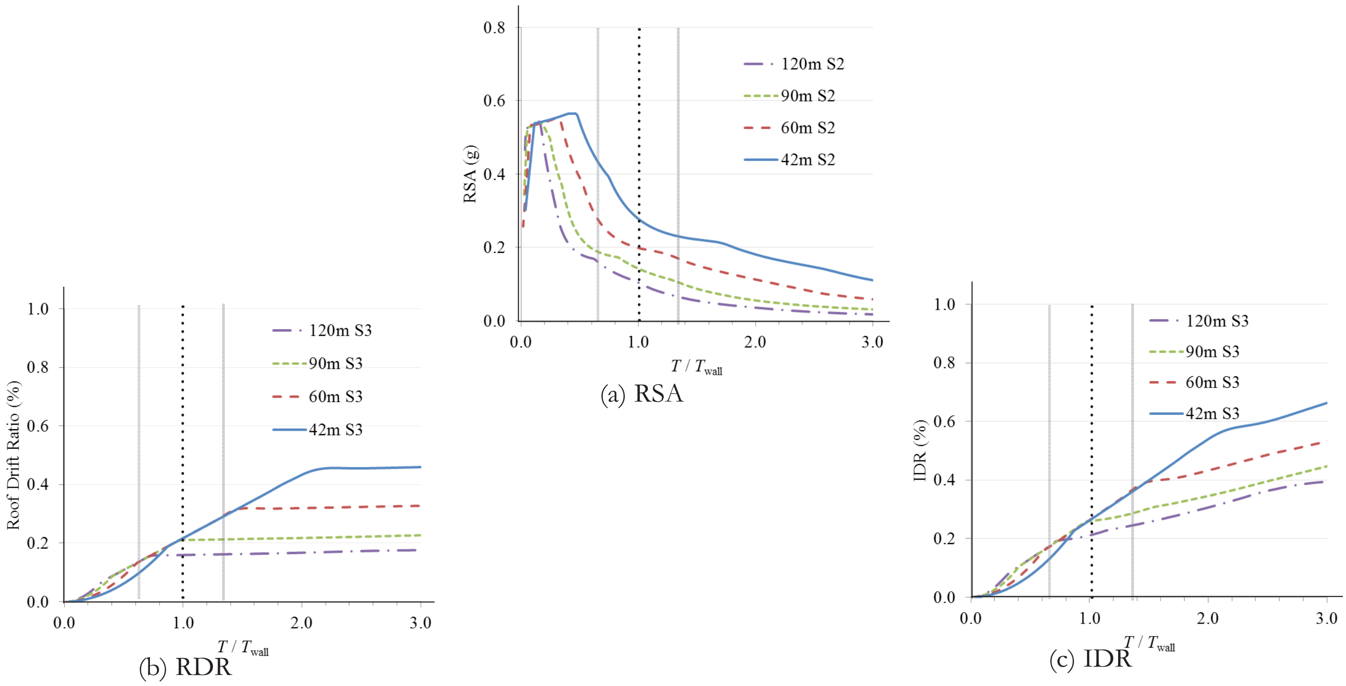


Figure 8 Seismic Demands of Wall Buildings ($r_{sf} = 10$; $\beta_i = 1.414$; $\lambda_T = 1$; $\lambda_{irreg,d} = 1$)

mode natural period for medium-to-high-rise shear wall buildings (assuming r_{sf} = 10) under uni-directional earthquake action (for Site 2). The normalised lower-bound ($0.01H_b \cdot \beta_i$) and upper-bound ($0.02H_b \cdot \beta_i$) periods, with respect to the expected period ($0.015H_b \cdot \beta_i$), are 0.67 and 1.33, respectively. The expected RSAs for various building heights are within 0.28 g (T/T_{wall} = 1) for a 14-storey (42 m) building and 0.10 g for a 40-storey (120 m) building. For the 14-storey building, the RSA may vary between 0.23 g and 0.43 g for a range of possible first mode natural periods.

Figure (9a) shows the *RSA* with the normalised first mode natural period for low-rise frame buildings (assuming r_{sf} = 0.1) under uni-directional earthquake actions (for Site 2). The normalised lower-bound ($0.0244H_b^{0.75} \cdot \beta_i$) and upper-bound ($0.0488H_b^{0.75} \cdot \beta_i$) periods, with respect to the period of the pure RC frame building ($0.075H_b^{0.75} \cdot \beta_i$), are 0.33 and 0.65, respectively. Compared to high-rise wall buildings, the *RSA*s for short-period low-rise buildings with two to ten storeys are relatively larger. The *RSA*s for more flexible low-rise frame buildings are within 0.12 g (T/T_{frame} = 1) for a ten-storey building and 0.73 g (flat-top value) for a two-storey building. In the presence of RC and/or masonry infills, the period could be shorter (T/T_{frame} = 0.65 corresponds to Equation (3)) and a higher demand on the *RSA* ranging from 0.24 g to 0.73 g is expected for low-rise infilled frame buildings with two to ten storeys.

Based on the TB model and the *RSA* demands, the base shear (or storey shear) can be computed. As the design shear stress must not be greater than the shear stress capacity v_c:

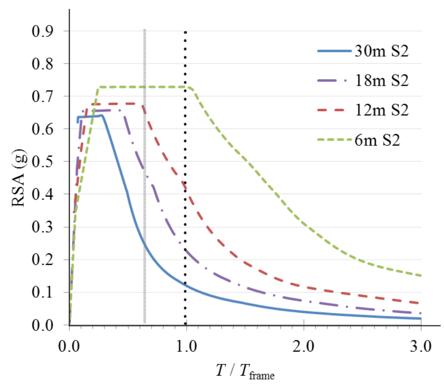
$$v = \Omega \lambda_{irreg} \lambda_{trans} \lambda_T \frac{RSA\,(A_F \sum_{i=1}^{n} m_{ud,i})}{0.8 \times \sum A_{w,j}} \leq v_c \qquad (9)$$

in which

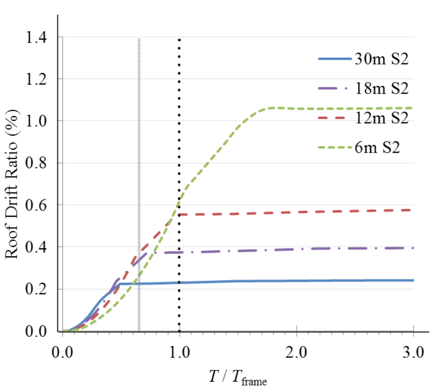
- Ω is the overstrength factor for shear that may be taken as 1.5;
- λ_{irreg} is the plan irregularity factor that may be taken as 1.7;
- λ_{trans} is the plan transfer structure factor that is taken as 1.0 for a building without transfer structures or 1.5 for a building with a well behaved transfer structure (Su et al. 2014b);
- λ_T is the topographic factor that varies from 1.0 to 1.4 (EC8, BSI, 2004a);
- A_F is the total floor area;
- $A_{w,j}$ is the sectional area of the j-th wall (and/or column) along the direction of the earthquake action concerned, it is multiplied by a 0.8 factor to account for the reduction for effective depth;
- $m_{ud,i}$ is the uniformly distributed mass per unit area (e.g. the mass at the i-th floor $m_i = m_{ud,i} A_F$).

From Equation (9), the minimum shear (wall) area ratio at the critical floors (e.g. the ground floor and the floor just above the transfer structure) can be derived as:

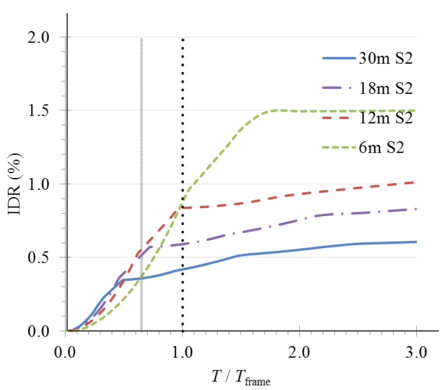
$$\frac{\sum A_{w,j}}{A_F} \geq \Omega \lambda_{irreg} \lambda_{trans} \lambda_T \frac{RSA}{0.8 \times v_c} \sum_{i=1}^{n} m_{ud,i} \qquad (10)$$



(a) RSA



(b) RDR



(c) IDR

Figure 9 Seismic Demands of Frame Buildings (r_{sf} = 0.1; β_i = 1.414; λ_T = 1; $\lambda_{irreg,d}$ = 1)

Once the RSA demands of buildings obtained from the design charts (Figure (8a) and Figure (9a)) and the corresponding parameters in Equation (9) are properly determined in accordance with the local conditions, the minimum shear area ratio demand can be computed. By comparing the minimum required shear area ratio and the design or existing shear area ratio of a building, its seismic performance can be evaluated.

RDR and IDR Demands

The RDR and IDR are the two important indices for evaluating the seismic performance of a building subjected to earthquake actions. For the collapse-prevention (CP) limit state, the RDR of 1% and IDR of 1.5% recommended by CSA (2004) are adopted. Such stringent limits are achievable in low-to-moderate seismicity regions only. Comparatively, the Vision 2000 report (SEAOC, 1995) suggests an IDR of 1.5% for the life safety (LS) limit state and 2.5% for the CP limit state. EC8 imposes a more stringent IDR limit of 0.5% to 1.0% on buildings that are attached to isolated non-structural components under 475-year RP earthquakes.

The RDRs for high-rise wall buildings with 14 to 40 storeys against normalised first mode natural periods (with respect to T_{wall}) are shown in Figure (8b), in which a constant RDR plateau is reached for normalised periods beyond 2. Moreover, a unified gradient trend for the RDR in Figure (8b) and IDR in Figure (8c) can also be observed. For the critical buildings with T/T_{wall} = 1.33, the maximum RDR and IDR are only 0.29% and 0.36% (Site 3), respectively, which indicates that limited nonlinearity is expected.

The displacement demands obtained from the design charts have to be amplified in the presence of unfavourable features: (a) a topographic factor $\lambda_T \geq 1.2$ is applied when the building is situated on a sloping site with a slope angle $\geq 15^\circ$; and (b) for irregular buildings, an irregularity and torsional factor for displacement demand, $\lambda_{irreg,d}$, ranging from 1.2 to 1.7, is applied for high-rise shear wall buildings (Su and Cheng, 2008; Tang and Su, 2014a). Thus, with these adverse conditions, the RDR for the expected period (T/T_{wall} = 1) is 0.45% (= 0.22%×1.2×1.7) and the IDR is 0.53% (= 0.26%×1.2×1.7). For flexible buildings (T/T_{wall} = 1.33), the RDR is 0.59% (= 0.29×1.2×1.7) and the IDR is 0.73% (= 0.36%×1.2×1.7). Particular cautions should be applied to more flexible medium-to-high-rise shear wall buildings under Site 3 conditions. However, these IDR values are below international limits (according to EC8 or the LS limit state of Vision 2000), indicating that high-rise shear wall buildings with 14 to 40 storeys could be able to sustain the occasional earthquake action, although slight damage to structural members and moderate damage to non-structural components could possibly occur according to the stringent requirement in EC8 (e.g. IDR > 0.5%).

Figures (9b) and (9c) show the RDR and IDR, respectively, with the normalised first mode natural period (with respect to T_{frame}) for low-rise buildings with two to ten storeys. The expected period for the low-rise infilled frames or RC shear wall buildings falls within T/T_{frame} = 0.33 and 0.65 as shown in Figure (2c). Thus the critical RDR and IDR demands at T/T_{frame} = 0.65 are 0.37% and 0.55% (Site 2), respectively. For low-rise pure frame buildings located on Site 2, the RDR at the expected period (T/T_{frame} = 1) falls within 0.23% and 0.62% and the IDR falls within 0.42% and 0.88%. If unfavourable features exist, the topographic factor (λ_T = 1.2) and irregularity factor ($\lambda_{irreg,d}$ = 1.7) should be applied. The critical RDRs would increase to 0.75% (= 0.37%×1.2×1.7) for T/T_{frame} = 0.65 and 1.26% (= 0.62%×1.2×1.7 for the two-storey building) for T/T_{frame} = 1. The critical IDRs increase to 1.12% (= 0.55%×1.2×1.7) for T/T_{frame} = 0.65 and 1.8% (= 0.88%×1.2×1.7 for the two-storey building) for T/T_{frame} = 1.

The results indicate that low-rise pure frame buildings with four storeys or less, located on Site 2 and coupled with unfavourable features, may be susceptible to damage (e.g. IDR = 1.8% ≥ 1.5% as required by Vision 2000 for LS limit state) if the ultimate IDR capacity of column elements is smaller than the seismic IDR demand. This could be the case for columns with non-seismic detailing or premature brittle shear failure (Su *et al.*, 2008; Zhu *et al.*, 2007). Detailed analysis is required to further assess the vulnerability of these low-rise pure frame buildings with notable nonlinear behaviour.

CONCLUSIONS

A versatile two-dimensional non-uniform Timoshenko beam (TB) model has been adopted to assess the seismic performance of high-rise RC walls as well as low-rise RC frame buildings. The design spectra for four typical site conditions in HK have been constructed for occasional earthquake with an RP of 475 years. Modal response spectrum analyses have then been performed on the calibrated TB model under various site conditions. Finally, basic design charts correlating the seismic demands (e.g. RSA, shear area ratio, RDR and IDR) to the fundamental translational period of various types of buildings have been developed as a convenient design tool for the preliminary seismic assessment of buildings. The results show that high-rise wall buildings with 14 to 40 storeys can sustain occasional earthquakes, but slight damage to structural members and moderate damage to non-structural components could possibly occur (e.g. Site 3). However, low-rise pure frame buildings without shear walls (which are rare in HK) with a height ≤ 12m, with unfavourable features under specific site condition (e.g. Site 2), may not meet the life safety (LS) requirement under the occasional earthquake action. The seismic performance of RC buildings in HK under the rare earthquake action with a RP of 2475 years will be investigated in the next phase of the study.

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BIOGRAPHY

Ray Su is an Associate Professor at The University of Hong Kong. His research interests include strengthening of RC structures and seismic modelling of concrete and masonry buildings. He has published over 200 technical publications in engineering mechanics and seismic engineering. He is serving as an editorial panel member for the Journal of Applied Mathematics, Structural Engineering and Mechanics, among others. He is currently involved in the development of seismic reinforced concrete details and design code for buildings in Hong Kong.

Dr. Chien-Liang Lee is a senior research assistant at the Department of Civil Engineering, The University of Hong Kong. His research interest includes seismic structural vibration control, system identification, seismic fragility analysis of buildings and floor micro-vibration measurement and control of high precision factories. In 2003 to 2009, he worked at the Department of Civil Engineering and Natural Hazard Mitigation Research Center, National Chiao-Tung University (NCTU, Taiwan) and was involved in many projects related to floor micro-vibration measurement and analysis of high-tech factories in Taiwan's science parks.

Mr. Tim O. Tang is a Ph.D. candidate at the Department of Civil Engineering, The University of Hong Kong. He received his B.Eng. in Civil Engineering from The University of Hong Kong in 2011. His current research is related to the development of simplified seismic assessment for RC structures in low-to-moderate seismicity regions.

Prior to joining Swinburne University of Technology as a Senior Lecturer, Dr. Hing-Ho Tsang taught and conducted research in earthquake engineering in Hong Kong and Germany. He was a consultant for the Hong Kong Housing Authority and also involved in seismic analysis of the Hong Kong-Zhuhai-Macao Bridge. He is currently co-developing the first seismic design standard for Malaysia. He has authored or co-authored over 100 technical articles in earthquake engineering. His research achievement has won him six prizes and awards.

SURFACE MODIFICATIONS AND APPLICATIONS OF RECYCLED POLYETHYLENE TEREPHTHALATE (PET) FIBRE FOR CONSTRUCTION: A REVIEW

Jingjing Jia[1], Pui-lam Ng[1,*], Hedong Li[1], Kai-tai Wan[2], Man-lung Sham[1], Kaimin Shih[3], Christopher Leung[4]

[1] *Nano and Advanced Materials Institute Limited, The Hong Kong University of Science and Technology, Hong Kong*
[2]*Department of Mechanical, Aerospace and Civil Engineering, Brunel University, London, United Kingdom*
[3]*Department of Civil Engineering, University of Hong Kong, Pokfulam, Hong Kong*
[4]*Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong*

A substantial amount of polyethylene terephthalate (PET) is consumed all over the world. From the economic and ecological perspectives, recycling PET waste to regenerate fibres for incorporating into concrete and/or mortar is presumably one of the most effective ways to minimise the disposal of plastic waste. It is envisaged that the incorporation of PET fibres into cementitious materials can achieve higher ductility, higher fracture toughness, better crack control and crack bridging properties. However, recycled PET fibres have intrinsically poor wettability and weak adhesive bonding with cement paste, and it would be degraded in the alkaline environment of cementitious matrix. There are mainly two approaches of surface modification to improve the bonding of recycled PET fibres with the cementitious matrix, namely (i) physical modification to proliferate the fibre roughness by surface crimping, hooking or twisting, and (ii) chemical modification to improve the hydrophilicity of fibre surface and to enhance the alkaline resistance of PET fibres. This paper summarises the physical and chemical approaches of surface modification and compares their effectiveness respectively, in order to develop the optimum surface modification strategy for the application of recycled PET fibres in cementitious materials..

Keywords: cementitious materials, polyethylene terephthalate fibre, recycling, surface modification.

INTRODUCTION

Polyethylene terephthalate (PET) has been widely used in various fast-moving consumer plastic goods, particularly beverage containers and bottles. However, the huge amounts of used PET commodities increase the burden on the public landfills and lead to severe environmental problems. To minimise the disposal of PET, there has been an increasing pressure for recycling and reusing PET waste. Identifying proper ways to utilise the recycled PET can undoubtedly contribute to resolving the acute problem of municipal solid waste accumulation. On the other hand, cementitious materials including concrete and mortar are the most widely used construction materials. Therefore, the incorporation of recycled PET fibres as micro-reinforcements in cementitious materials has attracted vast research aiming to consume the PET waste.

Cement-based materials are in general brittle and have low tensile strength, low energy absorption and weak crack resistance. The incorporation of fibres to form fibre-reinforced cementitious composites has been shown to enhance the tensile capacity, fracture toughness, and crack resistance of cementitious materials (Dubey, 1999). The underlying principle is that the discrete reinforcing fibres can prevent crack propagation by transferring tensile stress across the crack to tension along the fibres, as well as to the bond between the fibres and the cementitious matrix. This crack bridging mechanism can increase the energy absorption in the post-crack regime and promote ductile fracture of the cement-based composites (Dubey, 1999; Sujivorakul, 2002). Hence, the effectiveness of using recycled PET discrete fibres to produce fibre-reinforced cementitious materials is an important area of research.

The energy absorption of a fibre-reinforced cement-based composite is dependent very much on the bond characteristics of the fibres with the cementitious matrix. It is because the bond slip between the individual fibre and the cementitious matrix would dissipate substantial amount of energy during the crack propagation process. The bond behaviour is influenced by various factors, including the material properties of the cementitious matrix, the geometry and surface properties of the fibres (Guerrero 1999, Sujivorakul 2002). Therefore, the bonding characteristics of recycled PET discrete fibre in cementitious composites must be duly engineered to ensure the functionality of the material.

*puilamng@nami.org.hk Dr. Pui-lam NG

Generally speaking, PET fibre exhibits low surface energy and limited chemical reactivity, resulting in poor wettability and weak adhesive bonding of PET fibres as micro-reinforcements in cementitious matrix. Moreover, the recycled PET fibres would be degraded in the alkaline environment of cementitious matrix. Therefore, proper surface treatment procedures must be performed to achieve adequate interfacial adhesion and to prevent undesirable degradation of fibres. There are mainly two approaches of surface modifications to improve the bonding characteristics of recycled PET discrete fibres. The first approach is physical modification in proliferating the surface roughness of fibres in crimped, hooked, or twisted shapes; and the second approach is chemical modification in improving the hydrophilicity of the fibre surfaces and to enhance the alkaline resistance of the fibres. In fact, the introduction of new functional groups via chemical modification is potentially to alter both the physical and chemical nature of the fibre surface concurrently. By choosing the appropriate experimental parameters, it is possible to restrict the chemical modification to the surface of fibre, while leaving the interior structure unaltered (Avny and Rebenfeld 1986).

In this paper, the physical and chemical approaches of surface modification of recycled PET discrete fibre are reviewed and their effectiveness are compared. This is imperative to the development of optimum surface treatment and surface modification strategies for application of recycled PET fibre in cementitious materials.

RECYCLING AND SURFACE MODIFICATION OF PET FIBRE

PET is a thermoplastic which can be remelted under high temperature. During the recycling of PET wastes, the PET is cleaned, melted, and reformed by extrusion. The resulting recycled PET continuous fibre would be chopped into discrete fibres. In the following, the manufacturing processes of recycled PET fibre are introduced, and an account of physical and chemical modifications of recycled PET fibre is presented.

Regeneration of PET fibres

Fibres with circular or rectangular cross-sections are commonly regenerated from recycling of PET wastes. This section describes the processes involved in the regeneration of PET fibres.

- Fibre with circular cross-section

After the cleaning and melting process, the fibres are extruded from a nozzle at the tip of the extruder, which is typically disk-shaped and has a number of small holes. The temperature is set at 250-280°C during the extrusion process for PET to melt. PET fibres with circular cross-section are extruded from the nozzle. The resulting recycled PET continuous circular cross-section fibres (or monofilaments) are then indented and cut into discrete fibres, as shown in Figure 1. The fibres are further drawn in a water bath with cooling water (Ochi *et al.* 2007).

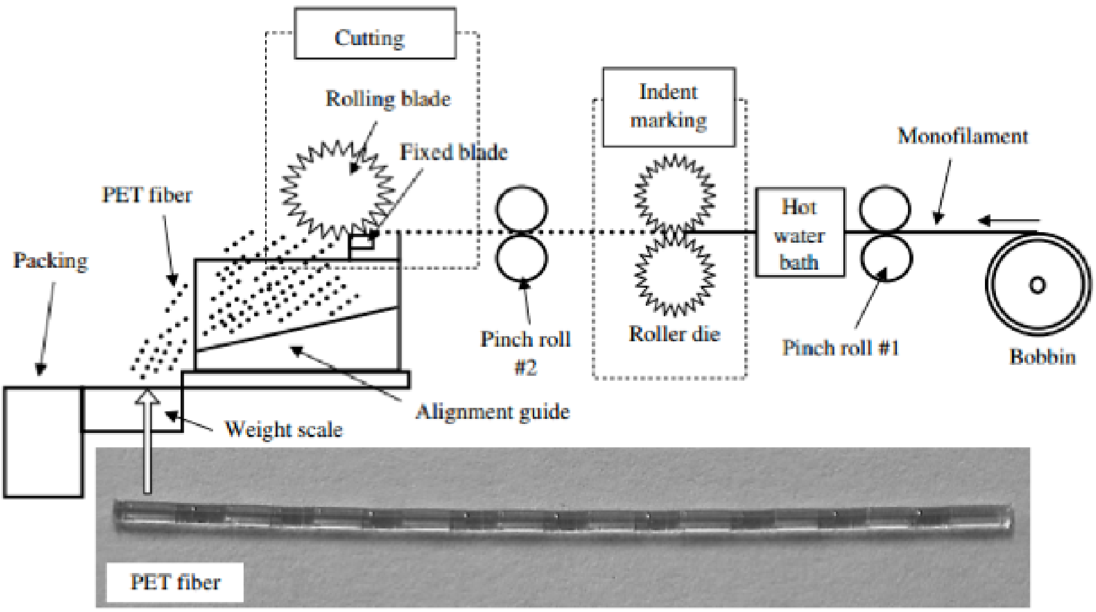


Figure 1 Apparatus of the indent marking and cutting of PET fibre (Ochi *et al.* 2007)

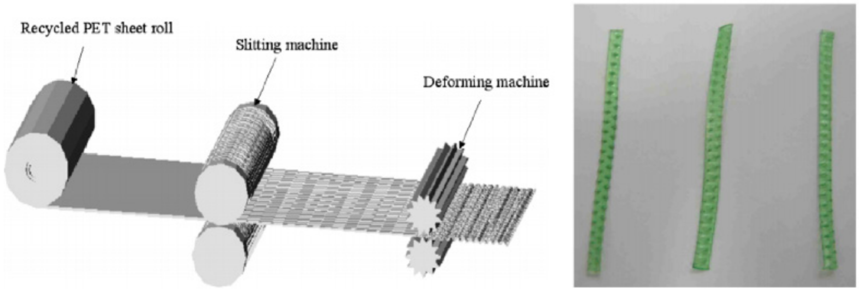


Figure 2 Process for manufacturing rectangular cross-section fibres from recycled PET bottles, and the appearance of resulting PET fibres (Kim *et al.* 2008)

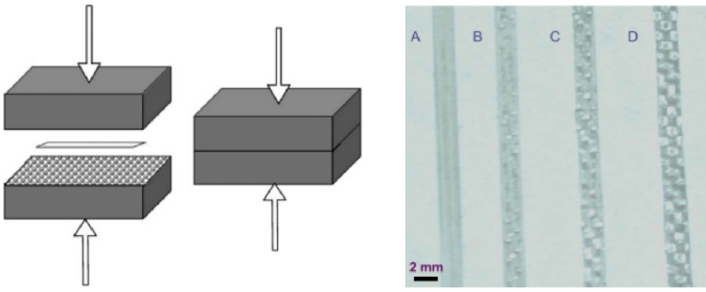


Figure 3 Schematic of indentation procedure by pressing (left) and the appearance of pressed PET fibres (Singh *et al.* 2004)

• Fibre with rectangular cross-section

The recycled PET is firstly melted to form a roll-type sheet. The sheet was then slit into continuous fibre strips with rectangular cross-section of 0.2-0.5 mm thickness and 1-5 mm width, and a deforming machine was used to change the surface geometry of each continuous fibre strip (Figure 2). Finally, the continuous fibres were cut into discrete rectangular cross-section fibres of 20-50 mm length (Kim *et al.* 2008).

Physical modification

In general, the freshly extruded PET fibre with circular or rectangular cross-section is smooth and would have relatively low pullout resistance from the cementitious matrix. The emphasis of physical modification is to produce various indents on fibre surface to increase the surface roughness of the resultant PET fibres.

For the PET fibres with circular cross-section, the indents can be produced by indent roller die. The PET monofilament is commonly preheated in a hot-water bath under 68-73°C before indentation. This processing temperature is close to the glass transition point of PET, and the control of temperature is critical for the consistency of the sizes of indents. For those fibres with rectangular cross-section, different indentation shapes can be used, including straight, "O" fibres, crimped and embossed. Several mechanical indentation methods have been developed to increase the surface roughness of PET fibre strips. One of the methods is to modify the continuous PET sheet by a two-roller system with projections, as shown in Figure 2. The extruded sheet is passed through while pressed at the required load by finely adjusting the distance between the two rollers. The resulting sheet with indentations can be slit longitudinally into strips, which may be further cut into desired length. Another method is to press the fibre between two hardened steel surfaces with projections, as illustrated in Figure 3. Different levels of pressure and surface morphology of indentation could also be chosen (Singh *et al.* 2004).

Won *et al.* (2011) investigated the effects of PET fibre shapes on the pullout behaviour of cement-based composites. The bond strength of the embossed fibre was about 5 MPa and was significantly superior to the crimped and straight fibres. A linear relationship exists between the pullout load and displacement until the fibre and cement matrix begins to debond, subsequently with a nonlinear relationship until the fibre was finally pulled out or fractured, as illustrated in Figure 4. Similar patterns were observed for all the three fibre types, with the difference in displacements. The straight fibre manifested the shortest linear portion before reaching the maximum pullout load with small displacement due to the rapid debonding between the smooth fibre and the cement matrix. Comparatively, the embossed fibre showed an extended nonlinear portion derived from the uneven surface and the straightening of the fibre over the fibre-matrix interface. This gives rise to

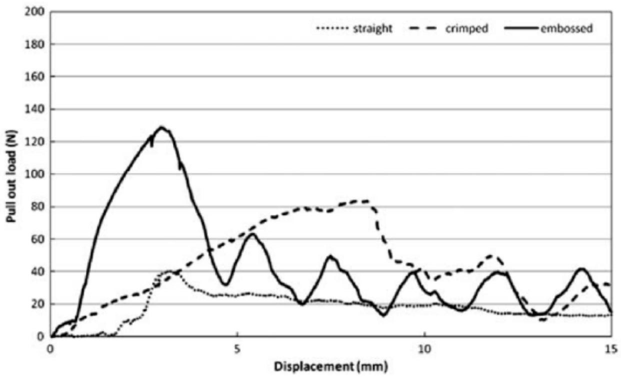


Figure 4 Pullout force versus displacement curves of three types of indented PET fibres (Won *et al.* 2011)

a constant resistance to the pullout load until final pullout or fracture of fibre was reached. As for the crimped fibre, it was difficult to distinguish whether the peak pullout load occurred at the linear or nonlinear regime. When the fibre was under loading, the crimped sections started to unfold before reaching the maximum pullout load. The more the fibre unfolds, the larger the displacement at maximum pullout force would result.

Kim *et al.* (2008) examined the fibre surface after the pullout test to analyse the frictional resistant force due to different fibre shapes. The straight fibres had no significant signs of scratching, but with the presence of small amounts of adhered cement, due to the small surface area and low frictional resistance. In contrast, the surface of the embossed fibres was found to be scratched, and the embossed area was partly ripped out. The crimped area of the crimped fibres was laid open. The bond was strengthened as a result of the mechanical anchorage effect around the crimped area and its mechanical bond strength increased continuously as the crimp was opened, but stopped once it was completely opened. However, the crimped area was comparatively weaker than the other areas because of the intrinsic production procedures, and was partially damaged during the test.

Chemical modification

In the last decade, extensive research on the technologies of chemical modification of the PET fibre surface has been conducted. Several methods to improve the wettability and to provide stronger bond between the PET fibre and cement matrix have been advocated. The typical methods of chemical surface modification of PET fibres, including alkali treatment, plasma treatment and matrix modification etc., are summarised in Table 1.

- Alkali treatment

Alkali treatment is a simple and efficient way to modify the surface of recycled PET fibre. The presence of alkaline could increase wettability, as well as providing potential sites for the formation of covalent chemical bonds within the cementitious matrix. The reaction mechanism between PET and alkali solution is shown in Figure 5: PET undergoes nucleophilic substitution and is hydrolysed by aqueous sodium hydroxide. The hydroxyl ions would attack the electron-deficient carbonyl carbon group to form an intermediate anion. Chain scission follows and results in the production of hydroxyl and carboxylate end groups. Similar chemical reactions were reported by Zeronian and Collins (1989) for the alkali treatment of polyester.

In the case of polyester, the reaction with aqueous sodium hydroxide appeared to be not confined on the surface. As the chain scission reaction occurs, the reaction products dissolve in the solution and a fresh surface unveils, which is attacked in turn. Consequently, the fibre diameter is progressively reduced. There would be a loss in fibre tenacity and mass as the hydrolysis progresses. However, the decrease is small when a low concentration of alkaline solution is employed for treatment. All in all, it is important to investigate the durability of PET fibre in the alkaline environment of cementitious matrix. Table 2 summarised the detailed research of alkali treatment effects on the durability of recycled PET fibre.

Fraternali *et al.* (2013) studied the alkali resistance of the recycled PET strips subject to immersion in alkaline solution at 60°C for 120 hours. The alkaline solution contained 10 g of sodium hydroxide and 1 dm^3 of distilled water. The tensile strength of the immersed PET fibre was found to remain at 87% of the untreated one.

Machovic *et al.* (2013) evaluated the interfacial transition zone (ITZ) between fibres from waste PET bottles and cementitious matrix using environmental scanning electron microscope (ESEM) and Raman spectra. After alkaline hydrolysis at an elevated temperature, both the surface morphology and content of polar group of PET fibres were altered. The ESEM observation showed that the composites of PET fibres treated by NaOH hydrolysis

Table 1 Chemical modification of recycled PET fibre

Reference	Surface Modification Technology	Details	Characterisation
(Machovie *et al.* 2008)	Alkali	Refer to Table 2	
(Shao *et al.* 2001)	Silica fume		
(Wu and Li 1999)	Plasma	Four types of gas: argon, air, ammonia, and oxygen; treatment time: 1, 5 and 10 min	Pullout test
(Mancini *et al.* 2013)	Plasma	Plasma composition (oxygen and air), power (25-130 W), time (1 and 5 min)	Contact angle, Surface energy
(Jung *et al.* 2013)	Matrix modification (Styrene-butadiene latex)	Latex was added at 0, 5, 10, 15, 20 and 25% of the binder weight (wt %)	Pullout test, Microstructural analysis of fibre surface
(Cioffi *et al.* 2003)	Plasma	Plasma composition (oxygen), power (50 W), time (5, 20, 30 and 100 sec)	Contact angle, Tensile test
(Oh and Park 2014)	Matrix modification	Nanosilica and silica fume contents were added at 0-10% of the cement weight, latex was used at 15% of the cement weight	Microstructural analysis (SEM)
(Won *et al.* 2010)	Sulfuric acid	3% H_2SO_4, and 3% sodium sulfate (Na_2SO_4) solution for 30, 60, 90 and 120 days	
(Won *et al.* 2010)	Salt	3% NaCl and 4% $CaCl_2$ for 30, 60, 90 and 120 days	
(Won *et al.* 2011)	Surface coat	PET fibres were passed in maleic anhydride grafted polypropylene (mPP) solution of 5, 10, 15 and 20 wt % at 80 °C	

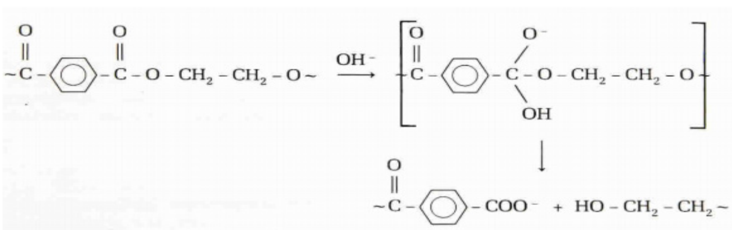


Figure 5 Chemical modification of PET fibre by alkali (Zeronian and Collins 1989)

Table 2 Alkali treatment of recycled PET fibre

Reference	Solution Concentration	Immersing Temperature and Time	Characterisation
(Machovie *et al.* 2008)	1M NaOH solution; saturated $Ca(OH)_2$ solution	90°C at a heating rate of 10°C/minute, and then left at ambient temperature for 3 days	FTIR, DSC, Water vapour absorption, Microstructure of fibre surface
(Shao *et al.* 2001)	10 wt % NaOH solution	60°C for 120 hours	
(Machovic *et al.* 2013)	1M NaOH solution	90°C at a heating rate of 10°C/minute, and then left at ambient temperature for 3 days	Raman spectra
(Ochi *et al.* 2007)	10 wt % NaOH solution	40, 60 and 80°C for 120 hours	Tensile strength
(Silva *et al.* 2005)	$Ca(OH)_2$ saturated solution (pH 12.3), 0.1 M NaOH (pH 13), and Lawrence solution (0.48g/l$Ca(OH)_2$ + 3.45g/l KOH + 0.88g/lNaOH, pH 12.9)	5, 25 and 50°C for 150 days	FTIR, Microstructural analysis (SEM equipped with EDX)
(Won *et al.* 2010)	pH 12.6 by mixing 0.16% $Ca(OH)_2$ + 1% NaOH + 1.4% KOH	30, 60, 90 and 120 days	Microstructural analysis (SEM)

Note: FTIR stands for Fourier transform infrared spectroscopy; DSC stands for differential scanning calorimeter; SEM stands for scanning electron microscope; EDX stands for energy dispersive X-ray spectroscopy.

had almost invisible ITZ, whereas the composites with non-hydrolysed PET fibres had distinct heterogeneous ITZ with a thickness up to 50 μm, as well as a profound abundance of large pores containing large crystals of portlandite and ettringite (Figure 6). Raman spectroscopy also showed that the most intensive bands of portlandite and ettringite appeared within the 50 μm ITZ from the hydrolysed PET fibre, while the cement composites with alkaline hydrolysed PET fibres did not show an increased concentration of the above mineral phases near the fibre surface.

- Surface hydrophilisation treatment

Won *et al.* (2011) reported the enhancement of bond performance between recycled PET fibre and cement matrix via hydrophilisation treatment with maleic anhydride grafted polypropylene (mPP). Different concentrations of mPP were employed and compared with control PET fibre without being subjected to surface treatment. It was shown that the pullout behavior, bonding strength and interfacial energy were increased along with the concentration of mPP up to 15%, and then decreased at higher concentration. Moreover, the hydrophilisation of recycled PET fibres enhanced the bond performance with the cement matrix by forming scratchings during the pullout process. As shown in Figure 7, the PET fibre surface after the pullout test with and without mPP treatment differed significantly. This is due to the strong hydrophilicity of mPP with cement matrix that upon pullout, induced scratches and even tearings at the PET fibre surface.

Park and Lee (2012) used styrene butadiene latex to improve the bonding properties of polypropylene fibre. Latex is a milky liquid containing surfactant-coated organic polymer particles, and it has been widely used in various cement-based composites requiring water tightness. The surfactant, such as ethoxylated nonylphenol and sodium dodecyl sulfonate, stabilises the particles and delays solidification, as well as increases the workability at a low water/cement ratio; while the latex particles form a film during hydration and fill the air voids. The test results showed that both bond strength and interface toughness increased with the latex content up to 15%. This is because the latex filled the pores and created a film that improved the bond strength between the components as well as increased the friction against pullout. Yet, the bond strength and interface toughness would decrease under latex content of 20% or more, possibly due to delay in the hydration reaction.

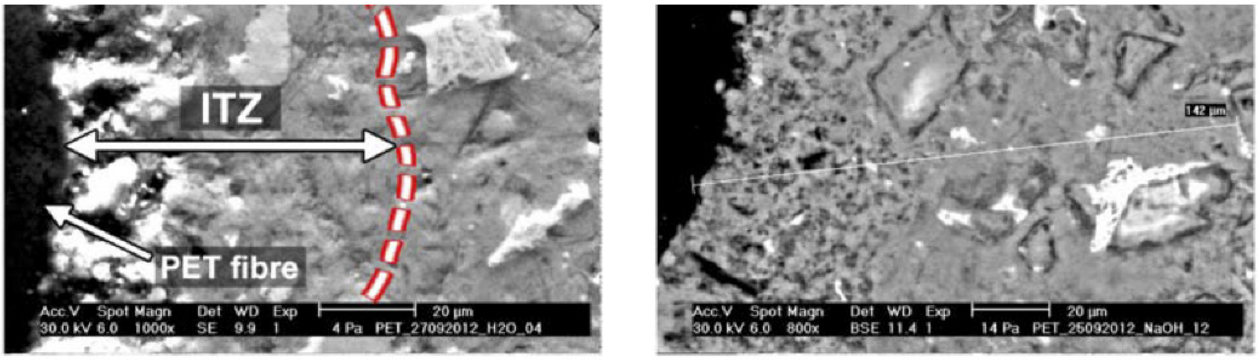
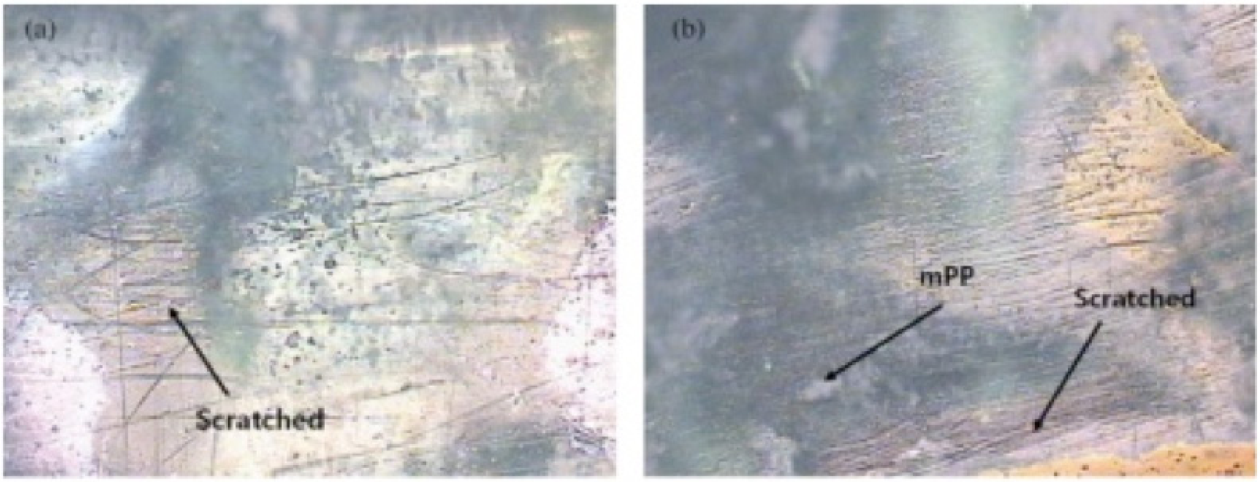


Figure 6 ESEM images of the cementitious matrix and ITZ around a non-hydrolysed PET fibre (left) and a NaOH-treated PET fibre (right) (Machovic *et al.* 2013)



(a) control

(b) mPP at 5% content.

Figure 7 Optical images of the PET fibre surface after pullout with and without mPP treatment

Table 3 Contact angle and surface energy and its components of oxygen plasma treated and untreated PET fibre (Cioffi *et al.* 2003)

Treatment	**Contact angle (°) (±1.5°)**	**γ_{sl} Harmonic (J)**	**γ_{sl} Geometric (J)**	**W_a (J/cm2)**
0	90			
O_2 5	31	7.3×10^{-6}	6.7×10^{-6}	13.5×10^{-6}
O_2 20	7	8.1×10^{-6}	7.5×10^{-6}	14.5×10^{-6}
O_2 30	9	8.3×10^{-6}	7.6×10^{-6}	14.5×10^{-6}
O_2 100	8	8.4×10^{-6}	7.6×10^{-6}	14.5×10^{-6}

Table 4 Detailed information of recycled PET fibres added to concrete or mortar

Reference	W/C	Volumetric content of fibres (wt%)	Fibre length (mm)	Cross-section: Circular: diameter (µm)	Cross-section: Rectangular: width × thickness (mm)	Fibre surface condition
(Machovie *et al.* 2008)	0.4	2	10	26.7		Smooth
(Shao *et al.* 2001)	0.29-0.38	2.2	6	30		Smooth
(Wu and Li 1999)	0.3			38		
(Jung *et al.* 2013)			30	1000		Hydrophobic
(Machovic *et al.* 2008)	0.5	2	10	200		
(Foti 2011)	0.7	0.26	32 (strip); 30-50 ('O')		5 (width)	Strips and "O" fibre
(Fraternali *et al.* 2011)	0.53	0.5, 0.75, 1.0	40-52	700-1100	0.8×1.3 (oval)	Straight, crimped, embossed
(Fraternali *et al.* 2013)			11.3-35		0.5×2	Smooth
(Kim *et al.* 2008)	0.55	0.1-1.0	50		0.5×1	Straight, crimped, embossed
(Kim *et al.* 2010)	0.41	0.5-1.0	50		0.2×1.3 (embossed); 0.38×0.9 (crimped)	Crimped, twisted, embossed
(Machovic *et al.* 2013)	0.4	2	10	290		Alkali-treated
(Ochi *et al.* 2007)	0.5-0.65		30, 40	750		
(Oh and Park 2014)	0.47		30	1000		Straight and smooth
(Pereira de Oliveira and Castro-Gomes 2011)		0.5-1.5	35		0.5×2	
(Silva *et al.* 2005)	0.61	0.4-0.8	20	26		Alkali-treated
(Won *et al.* 2010)	0.5	*1.0*	50			Embossed
(Won *et al.* 2011)	0.55		50		0.2×1.3	Straight, crimped, embossed

Microstructural analysis revealed that scratches on the fibre surfaces were increased after pullout, which was probably attributed to the enhanced adhesion against fibre pullout. The number of scratches increased with increasing latex content up to 15%. Meanwhile the bonding strength and interface toughness increased with latex content up to 15% as well.

• Surface activation by plasma treatment

The mechanism of surface modification of polymer fibres by gas plasma involves the removal of hydrogen atoms from the polymer backbone followed by the replacement with polar groups. Plasma is generated by gas molecules excited by a source of electrical energy. Under excitation, electrons are stripped from the molecules, producing a mix of highly reactive disassociated molecules. Various gases, including ammonia, air, nitrogen, argon, and carbon dioxide could be employed for producing plasma, and the interfacial bond strength can be readily doubled with exposure to plasma for only a few minutes (Hild and Schwartz 1992). Cioffi *et al.* (2003) used a cold oxygen plasma to etch the surface of recycled PET fibres. The results of contact angle, surface energy and work adhesion values for untreated

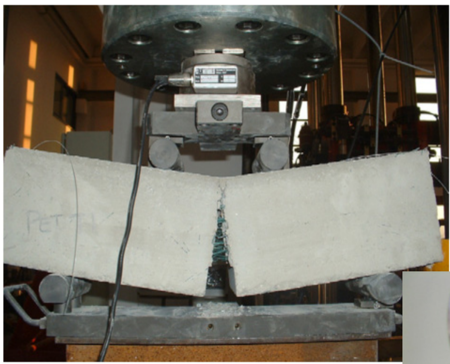
Table 5 Physical and mechanical performance evaluation of PET-reinforced concrete and mortar

Reference	Tensile test	Three-point loading: First-crack strength	Three-point loading: Toughness indices	Pullout test	Compressive test	Plastic shrinkage cracking	Water absorption	Porosity measurement
(Machovie *et al.* 2008)		√			√			√
(Shao *et al.* 2001)	√	√						√
(Wu and Li 1999)				√				
(Machovic *et al.* 2008)	√							
(Foti 2011)		√	√		√			
(Jung *et al.* 2013)				√				
(Fraternali *et al.* 2011)		√ (Four point)	√ (Four point)		√			
(Fraternali *et al.* 2013)		√	√					
(Kim *et al.* 2008)				√		√		
(Kim *et al.* 2010)		√ (Four point)	√ (Four point)		√	√		
(Machovic *et al.* 2013)								
(Ochi *et al.* 2007)		√	√	√	√			
(Oh and Park 2014)				√	√			
(Pereira de Oliveira and Castro-Gomes 2011)		√	√		√		√	
(Silva *et al.* 2005)		√	√					
(Won *et al.* 2010)					√			
(Won *et al.* 2011)				√				

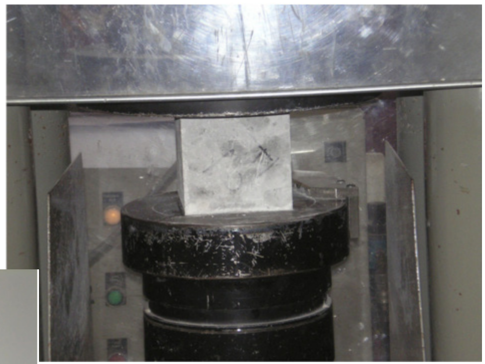
PET and oxygen plasma-treated PET with treatment time varied from 5 to 100 seconds are listed in Table 3, which showed the increased performance in both wetting and adhesion as the plasma treatment time was extended. Here, the decreased contact angle was a consequence of the interaction between the reactive species and oxygen plasma at the PET fibre surface.

PHYSICAL AND MECHANICAL PERFORMANCES OF RECYCLED PET FIBRE-REINFORCED COMPOSITES

To evaluate the roles of recycled PET fibre in cementitious materials, recycled PET fibre with different geometry and surface modification had been adopted to produce recycled PET fibre-reinforced concrete or mortar by various researchers. Various parameters including fibre length, diameter, surface modification, volumetric fraction of fibres, and water/cement ratio, as well as cement matrix modification were studied (Table 4). The physical and mechanical properties of concrete and mortar were assessed by tensile test, flexural test including three-point and four-point loading, single fibre pullout test, compressive test, plastic shrinkage cracking test, water



(a) flexural test (Kim *et al.* 2008)



(b) compressive test (Foti 2011)

(c) pullout test (Kim *et al.* 2010)

Figure 8 Setup for (a) flexural test (Kim *et al.* 2008), (b) compressive test (Foti 2011), and (c) pullout test (Kim *et al.* 2010)

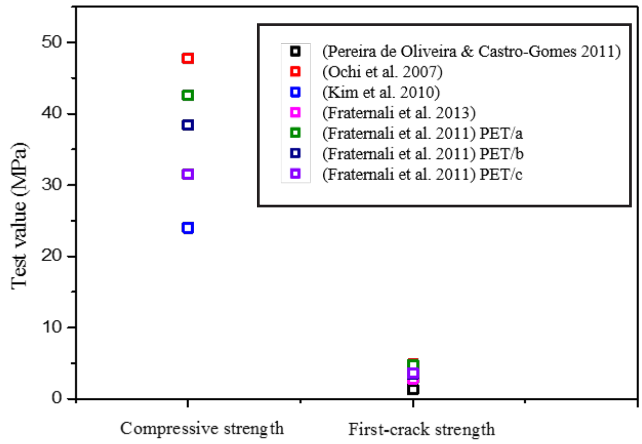


Figure 9 Compressive and first-crack strength of 1 wt% PET fibre-reinforced concrete and mortar

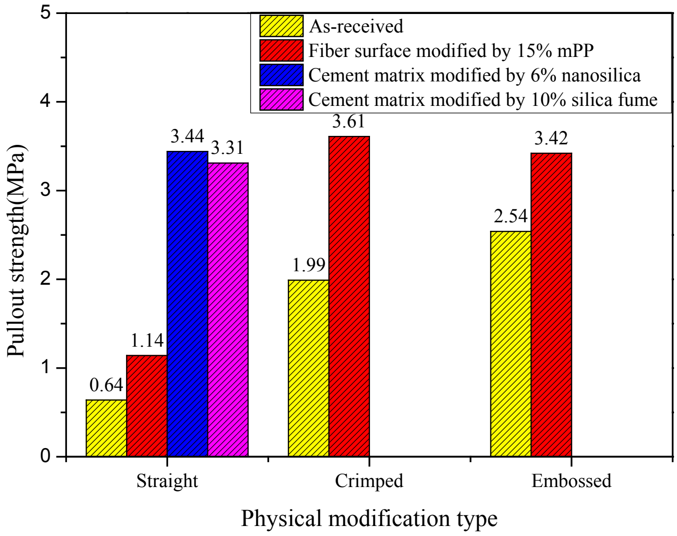


Figure 10 Effects of different chemical and physical modification methods on the pullout strength (Won *et al.* 2011, Oh and Park 2014)

absorption and porosity measurement (Table 5). Among these, the flexural, compressive and single fibre pullout tests (Figure 8) are typical methods to evaluate the effect of recycled PET fibre addition.

Flexural test

Flexural test with transverse bending is one of the most frequently employed tests to evaluate the mechanical performance of cementitious materials, in which a specimen with either a circular or rectangular cross-section is bent until rupture using a three-point or four-point loading configuration. The test is conducted in accordance with ASTM C1018. Figure 8(a) depicts the flexural test with four-point loading condition. The load versus displacement is used to measure the average values of the first-crack strength (f_{If}), toughness and residual strength factors. f_{If} is corresponding to the first peak of the load-deflection response. The toughness of each concrete or mortar specimen is measured through the area under the corresponding load-deflection curve, which is related to the energy absorption capacity of the material. Figure 9 shows the values of f_{If} of 1 wt% PET fibre-reinforced concrete and mortar obtained by different researchers.

Compressive test

The compressive test (shown in Figure 8(b)) follows the European standard EN 12390: 2009. Cube specimens of 100×100×100 mm dimensions are employed for the compressive test. The load is applied via two platens at the top and bottom of the specimen. Figure 9 shows the values of compressive strength of 1 wt% PET fibre-reinforced concrete and mortar reported by other researchers.

Single fibre pullout test

The single fibre pullout or bond test is shown in Figure 8(c) and the test conducted in accordance with the Japan Concrete Institute (JCI) standard SF-8 for experimental evaluation method of fibre bond with cementitious matrix. The bond strength of the fibre is calculated as:

$$\tau_{max} = P_{max} / \pi DL$$

where τ_{max} is the maximum pullout strength, P_{max} is the maximum pullout force, D is the fibre diameter and L is the embedded length of fibre. The toughness of the fibre-matrix interface is critical in enhancing the fracture energy and ductility of the fibre reinforced cementitious composite. The interface toughness can be determined by integrating the area under the pullout force-displacement curve. The displacement required to measure the interface energy in the JCI SF-8 standard is 2.5 mm. Figure 10 summarises the effects of different chemical and physical modification methods on the pullout strength of fibre-reinforced cementitious composites (Won *et al.* 2011, Oh and Park 2014).

CONCLUSIONS

The development of surface modification techniques of recycled PET fibres and their emerging applications have paved the way to the substantial usage of PET waste in cementitious materials. This paper has presented various surface modifications and illustrated the performances of the treated fibres as summarised below.

- The surface roughness of fibre has significant positive effects on the fibre pullout behaviour. Surface physical indentation of recycled PET fibre is a promising way to improve the mechanical performance of fibre-reinforced cementitious composite. Recycled PET fibre with embossed surface exhibits better adhesive performance compared to the smooth one. Other tailor-made surface geometries of PET fibres may be explored to evaluate their effects on the performance of cementitious composite.

- Chemical modification methods, including (a) grafting of the fibre surface by alkali or plasma treatment; and (b) deposition of small particles on the fibre surface such as maleic anhydride grafted polypropylene (mPP) or silica fume may improve the wettability of recycled PET fibre surface and its alkaline resistance in the cement matrix. The mechanism is by surface hydrophilisation, surface activation and the introduction of surface polar functional groups. Investigation of the appropriate degree of chemical treatment such as the concentration of reagents and the treatment time is needed for achieving the required alkaline resistance and desirable interfacial bond between PET fibre and cementitious matrix.

- The incorporation of recycled PET fibre in cementitious materials including concrete and mortar is advantageous. The merits of recycled PET fibre-reinforced cementitious composites include high ductility, enhanced fracture toughness, increased tensile strength and deformation capacity, good crack control and crack bridging properties. The surface modifications of recycled PET fibre can contribute significantly to the physical and mechanical performances of the cementitious composites. Further detailed research work to formulate the optimum application strategy of recycled PET fibre in cementitious materials is urgently needed.

ACKNOWLEDGEMENT

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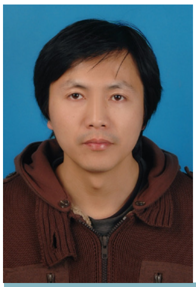
BIOGRAPHY

Dr. Jingjing Jia is an engineer at Nano and Advanced Materials Institute (NAMI), the Hong Kong University of Science and Technology. Her research interest is on the characterization of high performance fibers and interphase in polymer composite materials, and her recent emphasis is on surface modification of PET fiber to be applied in cementitious matrix under a research project funded by the Construction Industry Council (CIC).

Ir Dr. P.L. Ng is a technical manager at NAMI. He obtained his Bachelor of Civil Engineering and Doctor of Philosophy degrees at the University of Hong Kong. He is an honorary secretary and a fellow of the Hong Kong Concrete Institute. He has published more than 70 technical papers in the areas of concrete materials and structures. He has been awarded the HKIE Outstanding Paper Award for Young Engineers/Researchers in 2012, and Certificate of Merit, the HKIE Innovation Awards for Young Members by the Hong Kong Institution of Engineers in 2013.



Dr. Hedong Li is an Engineer at NAMI and he is also a lecturer in College of Civil Engineering and Architecture, Zhejiang University. His research interest is on the strain hardening multiple cracking cementitious composites, and his recent emphasis is on the development of Engineered Cementitious Composites with recycled PET fibers for waterproofing rendering matrix under a research project funded by the CIC.

Ir Dr. K.T. Wan is a lecturer in Civil Engineering of the Department of Mechanical, Aerospace and Civil Engineering of Brunel University London. His research interests are in green concrete, specialised concrete and repair materials as well as advanced sensor technologies and structural health monitoring.

Dr. Ivan M.L. Sham is the R&D Director overseeing the market segment of Construction and Building Materials in NAMI. He received his PhD in Mechanical Engineering from the Hong Kong University of Science and Technology and MBA from the University of Strathclyde (UK), with major in innovation management. His research interests include advanced fibre reinforced and nanostructured composites materials, surface modifications and finite element analysis. Dr. Sham has over 45 publications in international peer reviewed journals/ conferences, and 9 granted patents in United States/ Mainland China.

Prof. Kaimin Shih is an Associate Professor and leads the Environmental Materials Research Group at the University of Hong Kong. He obtained his PhD from Stanford University and is interested in engineering and employing material properties for innovative waste beneficial uses and treatments. He is an Associate Editor for Waste Management and an Editor for HKIE Transactions. He is currently the President for Overseas Chinese Environmental Engineers and Scientists Association, and the Secretary for Hong Kong Waste Management Association.

Prof. Christopher Leung is Head and Professor, Department of Civil and Environmental Engineering at HKUST. His major research interests include fracture mechanics, composite mechanics and the development and application of composite materials in civil engineering. He has published numerous research papers and has received awards and recognition from the American Society of Civil Engineers, the Chinese Ministry of Education and the Journal of Engineering Fracture Mechanics. Prof. Leung is currently Chairman of the Committee on Productivity and Research of CIC.

PLASTIC HINGE OF REINFORCED CONCRETE COLUMNS

Yu-Fei Wu[1,*], Cheng Jiang[1], Xue-Mei Zhao[1,2] and Jin-Song Wang[3]

[1]*Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong*
[2]*Building Diagnostic Consultants Limited, Kwai Chung, Hong Kong*
[3]*Fyfe (Hong Kong) Limited, New Territories, Hong Kong*

The behavior of plastic hinge in reinforced concrete (RC) is complicated and has not been well understood so far. Existing simple models of plastic hinge length have been widely used for design, evaluation, and construction of RC structures, such as for performance based designs and design of rehabilitation works. The existing models have been developed empirically from tests with limited scope, different emphases, and without a rational, systematic study of the problem. Furthermore, they do not include all the important factors and differ from one another in their predicted results, the factors they consider, and their forms. Therefore, one model is more accurate for one type of problem and another performs better in another case. The authors have investigated the problem through experimental tests, numerical simulations, and analytical studies, and have identified key factors that affect plastic hinge length. A more rational and accurate plastic hinge model is introduced in this article which is applicable to a wider range of structural applications.

Keywords: RC columns, plastic hinge length, modeling, retrofit.

INTRODUCTION

The history has shown that major earthquake disasters often occur in places that are not well prepared. From the historical lessons learned in past earthquakes, many earthquake experts, including the internationally renowned authority for seismic design of concrete structures, Professor Robert Park, has pinpointed Hong Kong to be earthquake vulnerable needing emergency planning for making its buildings earthquake resistant (Park and Paulay 2006). As a result, the Buildings Department is currently preparing for the introduction of statutory seismic design requirements for building development in Hong Kong. As pointed out by seismic experts, soft-storey failure of columns is a major problem in Hong Kong. External jacketing with fiber reinforced polymer (FRP) is currently the most effective, simplest and cheapest technology for RC column retrofitting. In fact, FRP jacketing is particularly effective in mitigating seismic damage of soft-storey structures, as it largely increases the ductility of RC columns, and hence, avoids strength degradation of structural members under very large earthquake displacement.

Flexural retrofitting of RC column involves wrapping of a layer of reinforcing material such as FRP and steel plate to the external face of a column within the plastic hinge region. By providing adequate confinement to a column through jacketing, the strength and deformation capacity of concrete can be largely increased, leading to a much improved performance of the retrofitted column in terms of both strength and ductility. Although controversies exist in the use of FRP materials in construction (e.g. on issues related to fire resistance, material brittleness, durability, and bond), FRP jacketing of RC columns has been least controversial compared with other FRP applications in construction, and hence, has been widely accepted as a highly reliable and effective construction method (Wu *et al*. 2006).

Flexural jacketing is required only at the plastic hinge region. Therefore, estimation of plastic hinge length is important. Although numerous plastic hinge length models have been proposed in the literature, various problems exist in these models and much more research works are needed (Jiang *et al*. 2014; Zhao *et al*. 2012).

PHYSICAL AND EQUIVALENT PLASTIC HINGES

The physical plastic hinge is the place in a flexural member where plastic deformation occurs. Plastic deformation can occur on the tension side of a column by yielding of reinforcing bars, and/or on the compression side due to large inelastic strain or crushing of concrete. Hence, the physical plastic hinge of RC members is defined as the region where concrete crushes or reinforcing bar yields. In the literature, the physical plastic hinge is often treated as the severely damaged region of a column (Bae and Bayrak 2008). Therefore for flexural retrofitting, only the physical plastic hinge region needs to be jacketed. To date, only limited number of investigations have been reported to determine the physical plastic hinge length (Ho 2003;

*yfwu00@cityu.edu.hk Dr. Yu Fei Wu

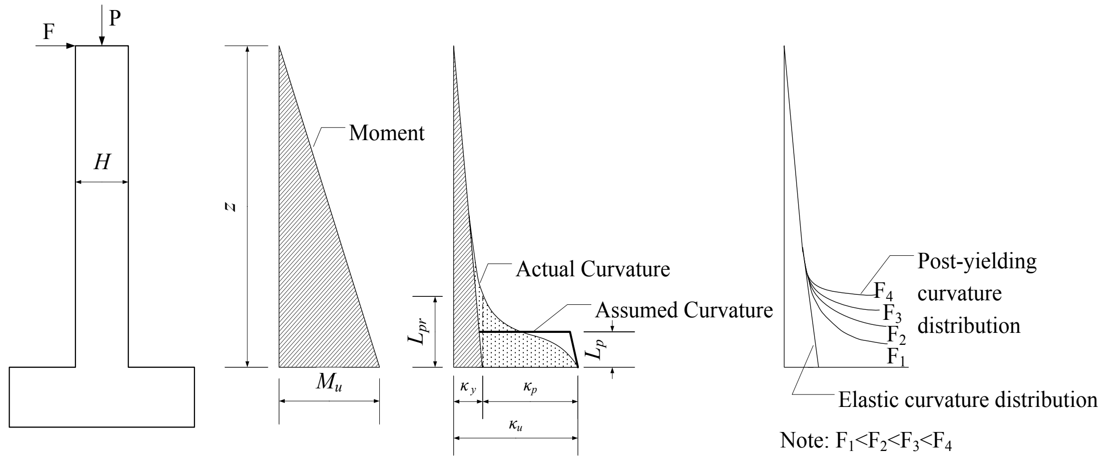


Figure 1 Plastic hinge lengths

Zhao *et al.* 2012; Jiang *et al.* 2014).

On the other hand, plastic hinge length is usually referred to the equivalent plastic hinge length in the literature rather than the physical plastic hinge length. In engineering design, the displacement of a flexural member is often calculated by integration of curvature κ along length, as in Equation (1).

$$\Delta = \int_0^z x\varkappa dx \tag{1}$$

where Δ is the displacement at the top of a cantilever column; z is the length of the column; x is the distance of a section from the column base. For simplification of engineering calculations, the plastic curvature is assumed to be concentrated in a region called the equivalent plastic hinge with a length of L_p. Therefore, the curvature distribution is represented by a linear elastic triangular distribution along the full height plus a constant plastic curvature in the plastic hinge region, as shown in Figure 1. Integration of this curvature distribution using Equation (1) gives (Paulay and Priestley 1992):

$$\Delta_u = \Delta_y + \Delta_p = \frac{\varkappa_y z^2}{3} + \varkappa_p L_p \left(z - \frac{L_p}{2}\right) \tag{2}$$

where Δ_u is the ultimate displacement; Δ_y and Δ_p are the yield and plastic displacements, respectively; κ_y is the yield curvature and κ_p the plastic curvature given by κ_u - κ_y (Figure 1), in which κ_u is the ultimate curvature. It can be clearly seen from Equation (2) that the equivalent plastic hinge length L_p largely affects the result of ultimate displacement. Rearranging Equation (2) gives

$$L_p = z - \sqrt{z^2 - 2\frac{\Delta_u - \Delta_y}{\varkappa_u - \varkappa_y}} \tag{3}$$

In the literature, empirical models for L_p are developed by determining the displacements and curvatures at the ultimate and yield points from experimental tests and calculating L_p using Equation (3).

It can be seen from Figure 1 that the physical plastic hinge length L_{pr} and the equivalent plastic hinge length L_p are different, and L_{pr} is generally larger than L_p. Hines *et al.* (2004) proposed the following relationship:

$$L_p = 0.5L_{pr} + L_{pb} = 0.5L_p + 0.022d_b f_y \tag{4}$$

where d_b and f_y are the diameter and yield strength of the longitudinal bars, respectively. The second term L_{pb} in Equation (4) allows for the yield penetration of steel bar into the column base.

EXISTING PLASTIC HINGE MODELS

Almost all existing plastic hinge models refer to the equivalent plastic hinge length. Baker (1956) firstly proposed an empirical plastic hinge model (Table 1). Up to now, more than twenty models have been proposed in the literature, as listed in Table 1.

Existing plastic hinge models are empirically regressed from experimentally obtained plastic hinge length. Most researchers including the renowned research group at the University of Canterbury have used Equation (3) to calculate the equivalent plastic hinge length from test results. In this case, the determination of ultimate and yielding displacements, Δ_u and Δ_y, and the corresponding curvatures, κ_u and κ_y are critical. The ultimate failure is often defined at the point of the post-peak load-deformation curve where the strength drops a certain percent, generally in the range of 10-30%. When different strength drops are used, the ultimate displacement Δ_u can be significantly different. The definition of yield point corresponding to Δ_y and κ_y could also be different in different works. As a result, the equivalent plastic hinge length calculated from

Table 1 Existing plastic hinge length models

No.	Reference	Model
1, 2	Baker(1956), Bate *et al.* (1962)	$L_p = k_1 k_2 k_3 \left(\frac{z}{d}\right)^{0.25} d \qquad k_1 = \begin{cases} 0.7 & for\ mild\ steel \\ 0.9 & for\ cold-worked\ ste \end{cases}$ $k_2 = 1 + 0.5\frac{P}{P_u} \qquad k_3 = \begin{cases} 0.6 & f'_c = 42MPa \\ 0.9 & f'_c = 14MPa \end{cases}$
3	Baker and Amarakone (1965)	$L_p = 0.8 k_1 k_3 \left(\frac{z}{d}\right) c$ $k_1\ and\ k_3\ same\ as\ in\ Model\ 2, c = neutral\ axis\ depth$
4	Sawyer (1964)	$L_p = 0.25d + 0.075z$
5	Mattock (1965)	$L_p = \frac{d}{2}\left[1 + \left(1.14\sqrt{\frac{z}{d}} - 1\right)\left[1 - \frac{q-q'}{q_b}\sqrt{\frac{d}{16.2}}\right]\right]$ $q = \frac{A_{st} f_y}{bdf'_c},\ q' = \frac{A_{sc} f_y}{bdf'_c}, q_b = \frac{A_b f_y}{bdf'_c}$
6	Corley (1966)	$L_p = \frac{d}{2} + 0.2\frac{z}{\sqrt{d}} \qquad (in\ inch)$
7	Mattock (1967)	$L_p = \frac{d}{2} + 0.05z$
8	ACI-ASCE (1968)	$L_p = \begin{cases} R_\varepsilon\left(\frac{d}{4} + 0.03 z_0 R_m\right) or\ R_\varepsilon d & lower\ bound \\ R_\varepsilon\left(\frac{d}{4} + 0.1 z_0 R_m\right) & upper\ bound \end{cases}$ $R_\varepsilon = \frac{0.004 - \varepsilon_{cue}}{\varepsilon_{cuo} - \varepsilon_{cue}}, z_0 = \frac{4M_m}{4V_z - \sqrt{wM_m R_m}}, R_m = \frac{M_m - M_e}{M_u - M_e}$
9	Park *et al.* (1982)	$L_p = 0.4d$
10	Mander (1984)	$L_p = 32\sqrt{d_b} + 0.06z$
11	Zahn (1985)	$L_p = (0.08z + 6d_b)(0.5 + 1.67n)\ n = 0.3 \quad when\ n \geqq 0.3$
12	Priestley and Park (1987)	$L_p = 0.08z + 6d_b$
13	Paulay and Priestley (1992)	$L_p = 0.08z + 0.022 d_b f_y$
14	Sheikh *et al.* (1994)	$L_p = 1.0d \quad (for\ high\ axial\ load\ level), h = depth\ of\ section$
15	Panagiotakos and Fardis (2001)	$L_p = \begin{cases} 0.12z + 0.014\alpha_{01} d_b f_y & for\ cyclic\ loading \\ 0.18z + 0.021\alpha_{01} d_b f_y & for\ monotonic\ loading \end{cases}$
16	Ho (2003)	$L_p = \left[20\left(\frac{P}{P_u}\right)^{0.5}\left(\frac{f'_c}{f_y}\right)^{1.5}\left(\frac{\rho}{\rho_s}\right)^{0.5} + 0.6\right] d$

Table 1 Existing plastic hinge length models

No.	Reference	Model
17	Ruangrassamee and Kawashima (2003)	$L_p = 0.2z - 0.1d$
18	Bae and Bayrak (2008)	$\frac{L_p}{d} = \left[0.3\left(\frac{P}{P_u}\right) + 3\left(\frac{A_{st}}{A_g}\right) - 0.1\right]\left(\frac{z}{h}\right) + 0.25 \geq 0.25$ $P_u = 0.85f'_c(A_g - A_s) + f_y A_s$
19	Berry (2006)	$L_p = \frac{0.05z + 0.1f_y d_b}{\sqrt{f'_c}} \leq \frac{z}{4}$
20	Berry *et al.* (2008)	$L_p = \begin{cases} 0.0375z + 0.12\frac{f_y d_b}{\sqrt{f'_c}} & \textit{optimal} \\ 0.05z + 0.1\frac{f_y d_b}{\sqrt{f'_c}} & \textit{recommended} \end{cases}$
21	Kolias *et al.* (2008)	$L_p = 0.1z + 0.015f_y^* d_b$
22	Alemdar (2010)	$L_p = \left[\frac{1}{4} + \frac{3f_y d_b}{10000\sqrt{f'_c}} + \frac{z}{25000}\right]d$ *based on deformation* $L_p = \left[0.3 + \frac{3f_y d_b}{10000\sqrt{f'_c}} + \frac{z}{5000}\right]d$ *based on curvature*
23	Biskinis and Fardis (2010)	$L_p = \begin{cases} 0.2d1 + \left[1 + \frac{\min\left(9; \frac{L_s}{d}\right)}{3}\right] & \textit{cyc. loading} \\ d\left[1.1 + \min\left(9; \frac{L_s}{d}\right)\right] & \textit{mono. loading} \end{cases}$
24	Gu *et al.* (2012)	$L_p = (0.59 - 2.30\lambda_f + 2.28\lambda_f^2)z + 0.022f_y d_b$
25	Köroğlu *et al.* (2014)	$L_p = -218.656 + 0.642f_{ys} + 0.201s - 0.07A_s + 0.001A_g + 2.544f_{co}$

Equation (3) could be significantly different.

On the other hand, some models such as that by Biskinis and Fardis (2010) do not allow for the effect of strain penetration into support (L_{pb} in Equation (4)). Also, some people developed the equivalent plastic hinge length model by measuring the physical plastic hinge region (severely damaged region) from tests (Bae and Bayrak 2008). Because of these differences, the empirical models reported in the literature can be very different in both the form and the results.

The factors that are considered in the existing plastic hinge models include (see Table 1): 1) cross-sectional depth H or effective depth d, 2) shear span length z or span-depth ratio z/d, 3) the type or yield strength of steel bar f_y, 4) concrete strength f_{co}, 5) axial load level P/P_u, 6) confinement effect by stirrups or external jacket, 7) diameter of tension bar d_b, 8) reinforcement ratios, 9) loading types (monotonic or cyclic), etc.

The above review of the existing literature shows that modeling of plastic hinge length is largely empirical and irrational so far. Furthermore, the methods for model development adopted by different people were inconsistent and the database used for model regression was both small and different. To date, the plastic hinge has not been well understood and modeled. In fact, the key factors that affect the plastic hinge length have not been correctly identified (Zhao *et al.* 2012). Further research works are very much needed.

RELEVANT RESEARCH WORKS AT CITY UNIVERSITY OF HONG KONG (CITYU)

We have evaluated the performance of the existing plastic hinge models using test data (Feng 2014; Jiang *et al.* 2015). The physical plastic hinge length L_{pr} was determined from the experimentally measured curvature distribution curve where the curvature is larger than the yielding curvature. The relationship between L_{pr} and L_p or Equation (4) was used to calculate L_p. A database was built by collecting test results from the literature (Ho 2003; Fedak 2012; Saadatmanesh *et al.* 1996; Zhao 2012; Jiang *et al.* 2014; Hose 2001). By comparing the model predictions with the test results in the database, it was concluded that the existing models give very different results and provide inadequate accuracy of prediction. Furthermore, none of them includes all the important factors.

To further study the plastic hinge problem, both experimental and numerical studies have been undertaken at CityU in recent years. Different methods have been investigated to increase the ductility of the plastic hinge region, including (1) the traditional external jacketing (Wu *et al.* 2006; Gu. *et al.* 2010), (2) by inserting small bars into concrete (Wu *et al.* 2008), and (3) by casting a precast compression yielding block into the plastic hinge zone (Wu and Zhou 2011). As confinement significantly affects the plastic hinge region including the length of the plastic hinge, a new plastic hinge model that allows for the effect of external jacketing has been developed (Gu *et al.* 2012). This is the first plastic hinge model published in the literature that considers the effect of external confinement by jacketing. The study has also determined that confinement has both beneficial and adverse effects on plastic hinge length, and identified the reasons for the contradictory test results reported in the literature.

Considering the large number of factors that affect the plastic hinge and the high cost involved in column tests, finite element modeling (FEM) has also been adopted to study the plastic hinge of RC flexural members (Zhao *et al.* 2012). Due to the high nonlinearity and complication of the problem, no FEM study on RC plastic hinge was carried out before this work, and therefore, it was the first FEM modeling reported in the literature on RC plastic hinges. This FEM study qualitatively investigated the problem and successfully identified the key factors that affect the plastic hinge length.

In a most recent study, the difference between jacketing circular and square RC columns were studied experimentally and the plastic hinge model proposed in Gu *et al.* (2012) was revised and extended so that it is applicable to both circular and square columns (Jiang *et al.* 2014).

PLASTIC HINGE MODEL CONSIDERING THE EFFECT OF EXTERNAL JACKET

Advanced technologies have been used to investigate the RC plastic hinge at CityU (Figure 2). Digital Image Correlation (DIC) technology was adopted to capture the strain of the whole column surface so that the detailed strain field in the plastic hinge region was recorded continuously during testing (Figure 2a). To measure the rebar yielding zone without disturbing its bond with concrete, the strain gauges were installed inside the reinforcing bars rather than on the surface of the bars (Figure 2b). From the intensive strain measurements, the rebar yield and concrete crushing zones could be closely monitored in the whole loading process.

A typical curvature distribution obtained from the tests is shown in Figure 3. During loading, the curvature distributions outside the plastic hinge zone do not vary significantly after plastic hinge forms, however those in the plastic hinge region change largely, as shown in Figure 1. This principle was used to determine the length of the physical plastic hinge L_{pr}, as shown in Figure 3. The real curvature distribution is not as smooth as that in Figure 1,

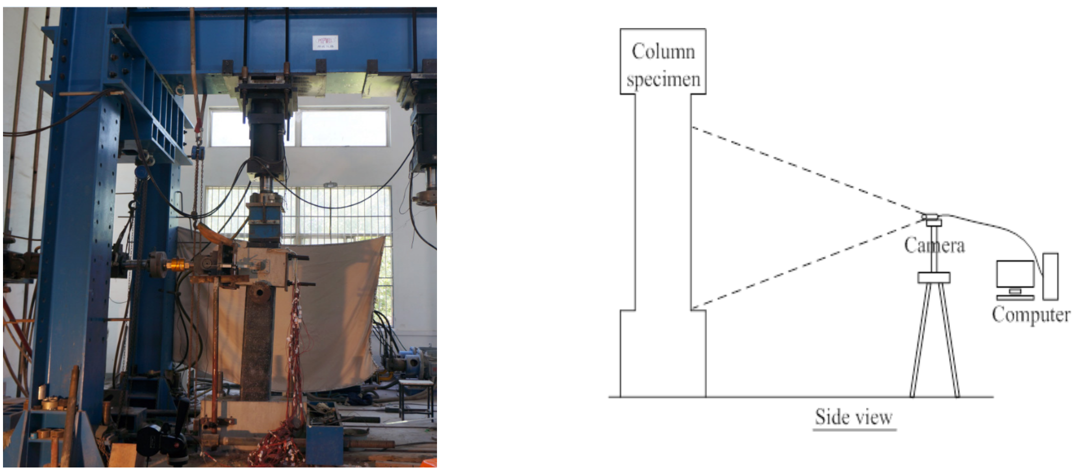


Figure 2(a) RC column tests - test setup and DIC system

Figure 2(b) Strain gauge installation

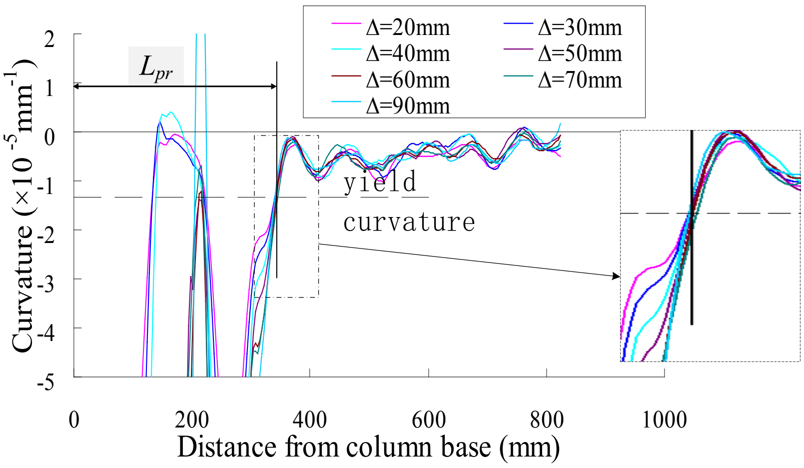


Figure 3 Typical curvature distribution

rather, it fluctuates along the column due to the existence of cracks. However, the dividing point between the curvature varying and non-varying zones can still be observed, which separates the plastic hinge region from the other part. It is noted that the dividing point determined in this way occurs exact at the location of yield curvature (Figure 3), which validates the rationality of the method.

Based on the experimentally determined plastic hinge length of the test columns, the following plastic hinge model has been developed (Jiang *et al.* 2014):

$$L_p = L_{p0} + \left(\frac{2r}{b}\right)^{0.72} \times L_{pc} \tag{5}$$

where

$$L_{p0} = 0.08z + L_{pb} = 0.08z + 0.022 d_b f_y \tag{6}$$

$$L_{pc} = \begin{cases} 3.028\lambda_f & when\, 0 \le \lambda_f < 0.1 \\ (0.51 - 2.30\lambda_f + 2.28\lambda_f^2)z & when\, 0.1 \le \lambda_f < 0.5 \end{cases} \tag{7}$$

$$\lambda_f = \frac{2 f_{frp} t}{b f_{co}} \tag{8}$$

in which b and r are the breadth and corner radius of the column cross-section, respectively; f_{co} is the strength of concrete; and t and ffrp are the thickness and strength of the FRP jacket, respectively.

The model and its performance are shown in Figure 4. It can be seen from the figure that the plastic hinge length is sensitive to the confinement of the jacket. The plastic hinge length increases at the beginning when confinement increases, and then reduces with further increase in confinement. This phenomenon is caused by two mechanisms. The first one is that FRP confinement leads to an increase in the compressive strength of concrete that causes an increase of the lever arm of the compression resultant and hence the moment resistance of the cross-section. In spite of the increase in the cross-sectional moment capacity, the yield moment does not change when confinement increases. As a result, the location of yield moment moves up when confinement increases, leading to a larger plastic hinge length. The second mechanism is that the lateral confinement from FRP jacketing increases the frictional bond between the longitudinal reinforcement and concrete. The bond stress opposes the bar stress and hence causes a reduction of the stress in the longitudinal bars, which reduces the rebar yielding zone. As a result, the plastic hinge length reduces. The first mechanism dominates in the ascending part of the curve in Figure 4, and the second mechanism governs in the descending part of the curve.

CONCLUSIONS AND FUTURE WORKS

The concepts of physical and equivalent plastic hinge

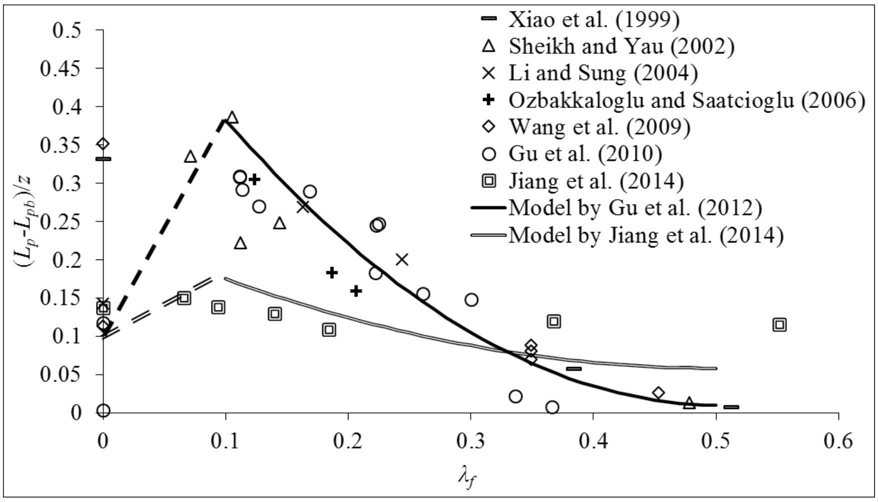


Figure 4 Performance of models (References in the figure refer to Jiang et al. 2014)

lengths are introduced. In seismic retrofitting, the determination of the physical plastic hinge region for retrofitting requires the knowledge of the physical plastic hinge length. The equivalent plastic hinge length is required to calculate the ductility and ultimate displacement of a flexural member. A review of extant literature shows that a satisfactory plastic hinge model is not available and much more research works are required to develop a more rational and accurate plastic hinge model.

Extensive investigations have been undertaken at CityU involving experimental testing, numerical simulation and analytical modeling. A more advanced plastic hinge model has been developed which allows for the effect of external jacketing, and hence, can be used not only for design of new RC columns but also for retrofitting of existing RC columns.

Further studies are going on at CityU, aiming at more detailed quantification of the tension yielding and compression yielding zones, and consequently, a more sophisticated and rational plastic hinge model in the future.

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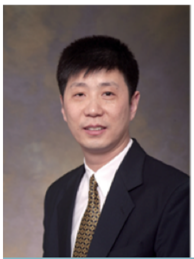
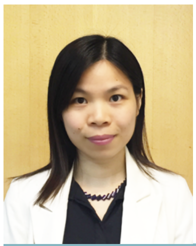
BIOGRAPHY



Dr. Yufei Wu is an Associate Professor in the Department of Architecture and Civil Engineering at City University of Hong Kong. He received PhD in 2002 from the University of Adelaide, Australia. Dr Wu has more than ten years of industrial working experience in structural engineering in China, Singapore and Australia and is a CPEng (MIPENZ, MIEAust). Dr Wu has published more than 100 technical papers and is the sole or 1st named inventor of 4 US patents.



Dr. Xuemei ZHAO is the General Manager of Building Diagnostic Consultants Limited (BDC). She obtained her Ph.D. from CityU specializing in experimental study and Finite Element Analysis of plastic hinge in RC structures. Dr. ZHAO is currently the Approved Signatory of BDC for construction material testing under the HOKLAS scheme. Her experience also involves applying advanced technologies such as Infrared thermography, radar imaging, and fiber optic sensors, in building/underground diagnosis, and structural health monitoring.

Mr. Cheng Jiang is a Ph. D. student at the Department of Architecture and Civil Engineering, City University of Hong Kong. He received his B. Eng in Civil Engineering from Southeast University (China) in 2011. His recent research interest includes the plastic hinge rotation of RC columns, FRP jacketing of column, bond behavior of FRP-to-concrete joints. He was a research assistant at CityU from 2011 to 2013.

Dr. Jinsong Wang is a Chartered Civil Engineer with over 20 years experience in the field of research and development, engineering consultancy and contracting. He specialises in the use of materials for civil and building works, durability design and repair of concrete structures. Dr Wang is the General Manager of Fyfe (Hong Kong) Ltd., a firm specialising in structural retrofitting and repairs. He is also a Visiting Professor to the Southeast University (Nanjing) and served in the past as the Honourary Secretary of the Materials Division of the HKIE.

PRELIMINARY STUDIES OF BUILDING ENVELOPE CONFIGURATIONS AND IMPACT ON THERMAL ENVIRONMENT

MinJung Maing[1,*] and Alan Lai[1]

[1]*School of Architecture, The Chinese University of Hong Kong, Sha Tin, N.T., Hong Kong*

The building envelope is the first barrier layer to separate indoor and outdoor environments. This layer that wraps the building typically includes some combination of solid opaque walls and windows. To make comparisons with building types, their layout and urban canyon effects, ratio of opaque walls to window areas and sky view factor (SVF) were mapped for various commercial and residential buildings in Hong Kong. The average window wall ratio in residential buildings was about 0.4 which is a prescribed ratio provided by ASHRAE 90.1, an international standard used for energy efficient design. A preliminary study was conducted on a typical building envelope type of a housing complex to compare how the urban canyon conditions, measured by SVF, for a given envelope emissivity would affect the thermal environment between the housing towers. The results showed that the amount of building envelope surface area receiving direct sunlight affected the measured radiation at the pedestrian level and consequently the mean radiant temperature (MRT). There are strong correlations with the MRT and sunlit view factor meaning that building orientation and urban canyon dimensions significantly affect urban outdoor thermal environment.

Keywords: building envelope, mean radiant temperature, sunlit view factor, window wall ratio.

INTRODUCTION

The exterior wall of the building, referred as building envelope, forms an important surface layer that controls our indoor thermal comfort from outdoor conditions. The envelope is a major component considered in sustainable design since it can provide shading, thermal resistance to control solar radiation and enhance indoor comfort. Much consideration is made in the design process to maximise these strategies but little consideration is taken on how the building envelope design will affect the outdoor thermal environment and the pedestrians within the adjacent outdoor space. Design strategies for the building envelope differ based on climate and can be generally summarised as: (a) block out heat, mainly direct solar radiation, for hot summer climates; and (b) maximise incoming heat, both direct and indirect solar radiation, for cold winter climates. Hong Kong, having a hot sub-tropical climate, experiences extreme hot weather over long periods throughout the year and primarily during the months of May to October. The envelopes that are reviewed in this research are residential and commercial buildings in Hong Kong's climate and with growing commitment to sustainability; the design of the envelope is aimed at blocking direct solar radiation entering the indoor using shades, using thick concrete walls of reflective colour and selectively using better performance windows. To study how the building envelope affects the outdoor environment, relevant parameters used to assess performance of envelope are identified. These parameters are: amount of incoming heat reflected back out – reflectivity, and amount of heat radiated or emitted – emissivity. In Hong Kong the performance of the building envelope is mainly measured by it OTTV (Overall Thermal Transfer Value) which is analogous to U-values used in other parts of the world. OTTV is targeted as a performance metric for commercial buildings and recently RTTV (Residential Thermal Transfer Value) has been recently introduced and in nascent stages of implementation. OTTV calculations use weighted average values of U-values for envelope and thermal absorptivity. However for considering envelope impact on outdoor environment, U-values and thermal emissivity are more appropriate parameters. In general low U-values are considered desirable for high performance envelopes which would translate to more radiation being reflected and emitted back into the environment.

The objectives of the research are: (i) to identify relevant design parameters of the building envelope that affect thermal outdoor environment; (ii) to conduct field study on urban areas with representative building envelope construction types to form correlations of the design parameters to mean radiant temperature, (MRT) and physiological equivalent temperature (PET); (iii) to conduct simulation studies to validate the simulation model with empirical data from field studies; and (iv) to formulate design assessment methods. PET and MRT are thermal indices used to study outdoor thermal comfort (Mayer H *et al* 1987, Chun Liang Tan *et al*, 2013, Spagnolo J *et al.*, 2003, Tze-Ping Lin *et al*, 2010). In the first stage, different types

*maing@cuhk.edu.hk Ms. MinJung Maing

of building envelope constructions were studied to identify categories relevant to its thermal performance and impact on urban environment. A pilot study was conducted on a representative building envelope type in a public housing estate in Hong Kong. The data collected during the field testing were analysed using regression methods to find correlations between identified test parameters. In this paper, work that has been done on parts (i) and (ii) of the research will be discussed.

METHODOLOGY

Envelope Characteristics and Configurations

To begin the research, information was gathered on existing envelope constructions, mapped against design configurations relating to material properties and building orientation in relation to ground and buildings. Buildings elevations were studied and grouped into residential and commercial building types. The key parameters of building envelope design and construction that are considered during design for desired envelope performance and its affect on outdoor environment were identified (see Table 1). Due to a relative homogeneity in most of the materials used in residential buildings, the configuration of how much exterior windows (glazing) and solid exterior walls (concrete) installed on the envelope were measured as ratios of Window Wall Ratio (WWR), and Opaque Wall Ratio (OWR), respectively. This consideration was also applied to commercial buildings.

Three configurations of building envelope construction were identified that could have potential affect on thermal environment: flat, recessed and protruded as shown in Figure 1. The flat envelope constructions were found with older public housing buildings of slab-type construction dated from around 1960s to 1980s and most commercial buildings. Recessed constructions are mostly seen in the newer public housing blocks and protruding constructions mostly in private housing blocks.

Pilot Study

The test site of Wo Che Estate in Sha Tin, New Territories was selected. This housing estate is a public rental housing complex with several twin tower block design, each

Table 1 Parameters used to study building envelope and urban environment.

Parameters		Definition and Description
WWR	Window-to-Wall Ratio	Ratio of the transparent glazing area to the outdoor floor-to-floor wall area (ASHARE, 2009) This does not include the metal frame and a general rule used was 80% of wall openings.
OWR	Opaque-to-Wall Ratio	Ratio of the opaque area to the outdoor floor-to-floor wall area (i.e., concrete surface)
SVF	Sky View Factor	Fraction of sky dome can be viewed from a particular point within canyon (Erell *et al.*, 2010).
ε	Emissivity	Fraction of radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature (Cengel, Y.A., 2003)
U-value	Thermal Transmittance	Overall heat transfer coefficient- usually a value referred to assess thermal performance of glass, of how much heat passes through the glass material. Low-emissivity glass has low U-values.
G_{solar}	Solar radiation	Energy (W/m^2) emitted by the Sun: about 99% of solar radiation lies between from 0.15 to 4.0 μm (Geiger, R, 2009) The total solar energy, namely 'global radiation' is the sum of 'direct' and 'diffuse' radiations. (Cengel, Y.A., 2003)
MRT	Mean Radiant Temperature	Uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure (ASHARE, 2009). MRT is obtained by measuring of all short- and long-wave radiant fluxes from six directions (namely up, down, right, left, front, back) (Sofia, T. *et al.*, 2007)

Figure 1 Three configurations of building envelope constructions that are representative of residential buildings in HK: flat, recessed and protruding.

(a) (b) (c)

Figure 2 Initial testing of long wave and short wave radiation at testing site at Wo Che Estate in Sha Tin HK. The testing locations are marked as A, B and C within the courtyard space between the three housing blocks.

consisting of two squares jointed at the corners and with a continuous open atrium in the center core of each square. There are usually 2 to 3 of these blocks in one cluster area. In Wo Che there are two clusters and each cluster has 3 twin tower blocks as shown in Figure 2a. For the first testing site, the flat envelope construction type and constant material emissivity and U-value were selected to focus the testing on investigating relationships between radiation, SVF and air temperature. Field-testing were conducted on three consecutive days of 31 December 2014, 2 January and 3 January 2015 at 3 locations A, B and C within the middle ground between the tower blocks, as marked in Figure 2b. Three net radiometers (one set up shown in Figure 2c) were set up to measure the long-wave and short-wave radiation from the six directions namely, from the sky dome, the ground, and the four cardinal directions (North, East, South and West). Concurrently, thermal images were taken with an infrared camera and fish-eye lens photos were taken every hour to calculate SVF.

RESULTS AND DISCUSSION

Construction Type and Envelope Configuration

The data collection of WWR and OWR of a sample of existing building envelopes comprising of public housing, private housing and commercial building types showed a trend of public housing buildings usually having lower window ratios than the other types. There was a tendency for commercial buildings to have all-glass walls, more notably in the recent developments, and for private housing towers to follow this trend. The public housing buildings tended to have lower WWR and within an average of around 0.4% as shown in Figure 3. Interestingly although there is no specific guideline prescribing window area on residential buildings, the public housing designs generally seem to comply with an international guideline of sustainability, ASHRAE 90.1 Section 5.2.1 which provides a PRESCRIPTIVE method requiring that "the vertical fenestration area does not exceed 40% of the gross wall area for each space-conditioning category".

Urban Canyon and View Factors

The effect of SVF on air temperature or surface temperatures within urban area has been widely studied for decades so as to understand the relationships between urban geometry and urban heat island (UHI) intensity, especially the nocturnal cooling effect (Oke, 1981, Unger, 2004). Closer observations of the fish-eye photos showed the opportunity to further define the view factor components to not only sky and non-sky areas, but also to differentiate sunlit wall areas from the building facades.

Thermal Infrared Image

Thermal infrared images of building elevations were taken to identify effect of solar radiation on the envelope. The images captures the difference in radiant fluxes radiated from building facades between sunlit and shaded area caused by direct sunlight cast on building envelope (see Figure 4). In some cases, the difference in temperature of suncast and non-suncast (shaded) area can be as large as 12.5 degrees, meaning that radiation differences are about 61.6 W/m^2. Using similar method as used to calculate SVF, the sunlit area, hence the sunlit view factor (SLVF) value can be obtained from the RayMan software with fish-eye photos. This further segmentation of view factors introduces a parameter than can better describe thermal patterns of the envelope in relation to the built environment. The next question would be does this parameter, SLVF have correlations with the measured solar radiation at the pedestrian level and consequently to MRT.

Effect of View Factor on Long-wave Radiant Fluxes and MRT

In this study, the emphasis is put on the effect of sunlit view factor on the long-wave radiant fluxes and thus the mean radiant temperature (MRT) within the high density urban environment. The measured long-wave radiant fluxes at test points, A, B, and C were shown in Figure 5 including the long-wave flux calculated from air temperature data extracted from nearest HKO Sha Tin weather station. There are fairly strong relationships between a) Downward Long-wave flux-SLVF data pairs, b) Sum of all six directions Long-wave fluxes-SLVF pairs, and c) MRT-SLVF pairs all with $R^2 > 0.4$ and significance level of 0.001 (see Figure 6).

CONCLUSIONS

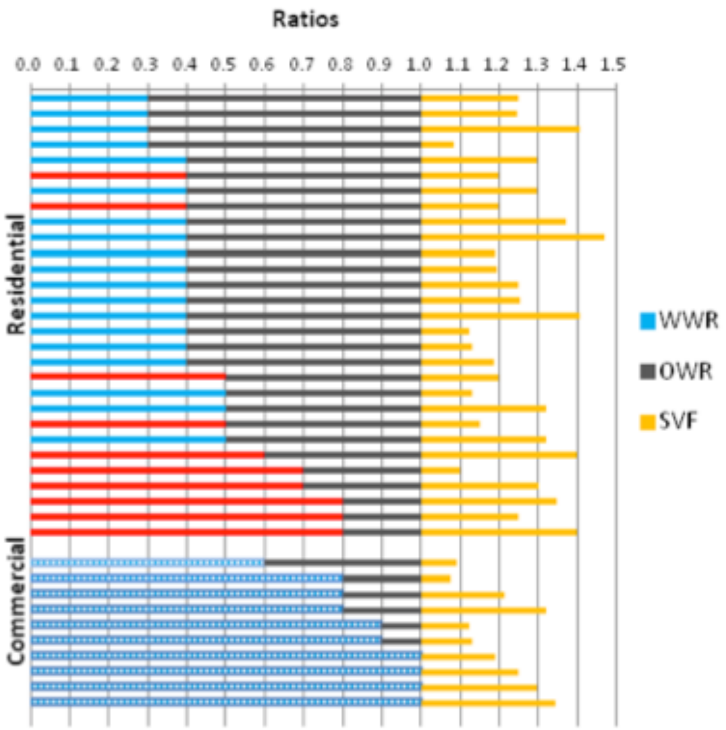


Figure 3 Window Wall Ratio, Opaque Wall Ratios and Sky View Factor distribution for sample of residential and commercial buildings. Solid blue lines represent WWR for public housing, red blue lines represent WWR for private housing and blue dashed line for WWR of commercial buildings

Table 2 Algorithm of Sky View Factor and Sunlit View Factor Calculation: fish-eye photos taken at the test site are processed with RayMan software

Fish-eye Photo	Sky View Factor	Sunlit View Factor
		
		
	SVF=0.35	SLVF = 0.075

Figure 4 Thermal infrared image of a partially suncast building envelope. The radiant temperature difference at the envelope surface between suncast and shaded wall surfaces on same wall ranges up to 12.5 degree, about 61.6 W/m^2 radiant heat flux.

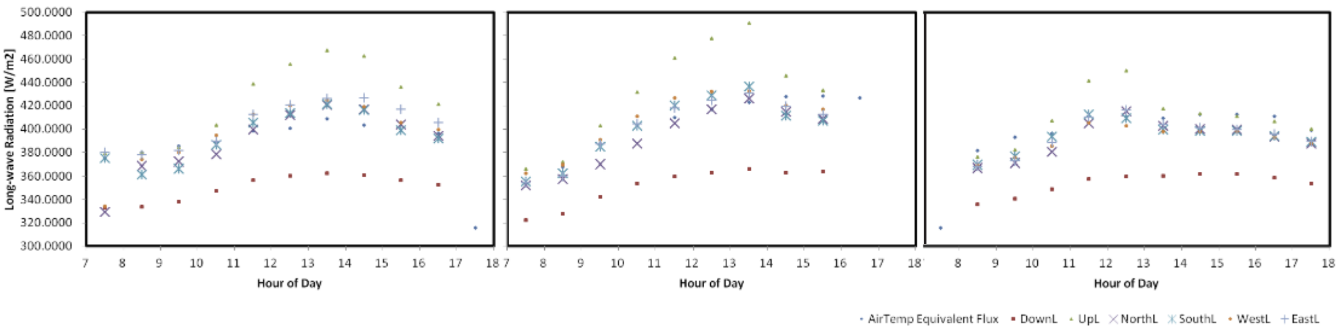


Figure 5 Air temperature comparisons in 6 cardinal directions for the three test points on 3 test days plotted against HKO temperature data for corresponding tested dates.

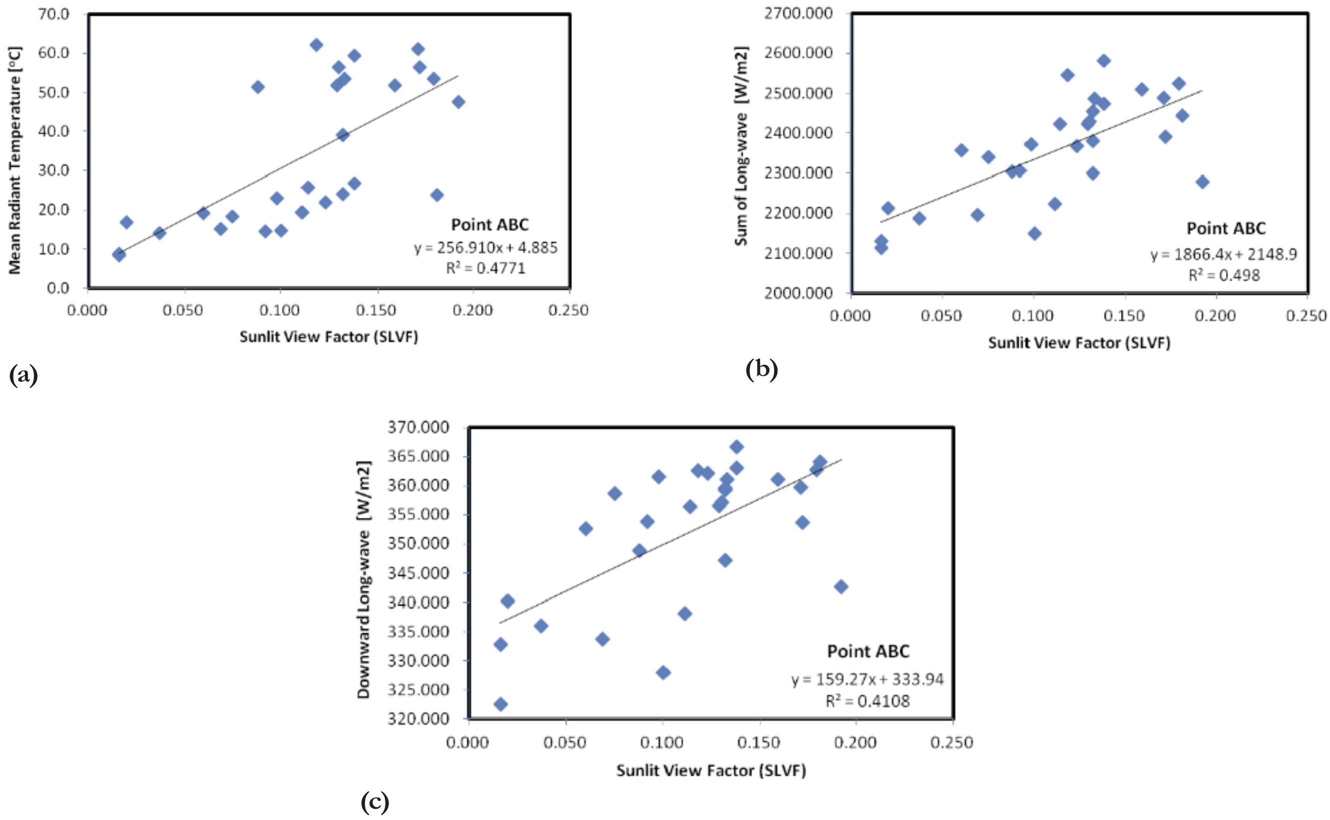


Figure 6 Regression analysis of sunlit view factor plotted against a) downward long-wave radiation, b) sum of long-wave radiation and c) mean radiant temperature.

The envelope construction of housing buildings have a large range of concrete to window ratios. Public housing blocks having an average WWR of about 0.4, meaning 40% windows and 60% solid concrete walls, some private housing blocks tend to be similar to commercial buildings in that the envelope has more window than solid wall (higher WWR). The first pilot test of a flat typical housing envelope with constant envelope emissivity, showed that the amount of direct solar radiation cast on the envelope has strong correlation with radiant heat flux at the pedestrian level in the public open spaces between buildings of the same envelope design.

Desired low U-values such as low emissivity glass, translates to larger reflected long-wave and short-wave radiation from vertical surfaces onto the urban outdoor environment. The next part of the research will do further testing to assess the sunlit view factor and radiation correlations with different envelope types and conditions. A comparison matrix will be developed to include tests and analysis with envelopes of differing glass-to-wall ratios, envelope configuration (recessed and protruding) and different layout within high-density urban areas (orientation).

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BIOGRAPHY

Prof MinJung MAING is Assistant Professor of School of Architecture at The Chinese University of Hong Kong. She conducts research on urban sustainability, thermal comfort, building design and construction performance metrics, and Building Information Modeling (BIM). She is interested in how building design affects urban environment and how design parameters can effectively integrate with building performance engineering and construction. She is a registered Architect and a licensed Professional Engineer, with degrees from Massachusetts Institute of Technology and Stanford University, USA.

Mr. Alan Lai is a Ph.D. student in the School of Architecture at The Chinese University of Hong Kong. He received his B.Sc. in Physics from CUHK. He worked as a research assistant in the Environmental and Sustainable Design Unit at the School of Architecture, CUHK. His research interests include modelling of solar radiation, radiation heat transfer, computational fluid dynamics, building science and outdoor thermal comfort.

Research Title	Practical Guidelines on Seismic Detailing for Concrete Buildings in Hong Kong	Labour and Cost Efficient Construction Method for Retrofitting RC Columns with FRP	An Empirical Study of Construction Time Performance of High-Rise Private Building Projects in Hong Kong	Innovative Design Technique for Steel-Concrete Composite Structures in HK	A Study of Impact of Building Envelope on Urban Outdoor Thermal Environment
Principal Investigator	Dr. K.L. Ray SU (The University of Hong Kong)	Dr. Yufei WU (The City University of Hong Kong)	Dr. Daniel CHAN (The Hong Kong Polytechnic University)	Dr. P.L. NG (Nano and Advanced Materials Institute Limited)	Ms. MinJung MAING (The Chinese University of Hong Kong)
Brief Description	To conduct a comprehensive investigation on the seismic ductility demands and capacities of RC structural members with special attention on the safety, necessity, effectiveness and constructability of the seismic details.	To transfer the academic and theoretical findings of model on the extent of RC column plastic hinge into practical construction guidelines for retrofitting of existing RC columns for addressing seismic issues.	To investigate the construction time performance of high-rise private building projects in Hong Kong, and thereby elevating the overall competition and productivity of the local construction industry as a whole.	To develop the ultra-ductile cementitious rendering for waterproofing and to optimize the extrusion condition and additives to transform the recycle plastic bottle to discrete fibre.	To investigate the changes in outdoor thermal environment induced by different building envelope systems to aid in the design decisions of building envelope in a high density urban context of Hong Kong.
Key Deliverables	1. Seismic analysis and design of RC buildings. 2. Practical guidelines on the seismic detailing of concrete buildings in Hong Kong	1. Efficient construction methodology and guidelines for minimised labor and construction costs of the retrofitting work for required seismic level.	1. Comparisons on construction time performance of projects between Hong Kong and Singapore 2. Summary of the determinants of project duration 3. Practical guidance notes for industrial practitioners for achieving efficient and faster project completion	1. A new generation of waterproof rendering material 2. Creation of local market for the recycle plastic bottles in Hong Kong to relief the pressure of limited landfill space 3. Demonstration to the industry about the practical application of waste utilisation	1. Scientific understanding of how the building envelope impacts urban thermal environment to designers 2. Solid data of the impact strength of general different building envelope types 3. Design strategies and practical suggestions / guidelines to aid building envelope design in improving the quality of urban thermal environment
Guideline / Patent	Y	Y	Y	Y	Y

CONSTRUCTION INDUSTRY COUNCIL
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ZCB
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Carbon Labelling Scheme for Construction Products
建築產品碳標籤計劃

Construction Industry Council has launched the Hong Kong based **Carbon Labelling Scheme for Construction Products** which aims to provide verifiable information on the carbon footprint of construction products for clients, designers, contractors and end users to select 'low carbon' materials.

建造業議會現已推出**香港建築產品碳標籤計劃**，為業主、設計師、承建商及消費者提供一個可驗證的建材碳足跡信息，以幫助其選擇「低碳」建材。

Initially, it covers three types of carbon intensive products:
計劃初步涵蓋三種較高碳排放的建材：

Cement
水泥

Reinforcing Bar
鋼筋

Structural Steel
結構鋼

Ready-mixed Concrete
預拌混凝土

A series of awareness and auditor courses are being organised by ZCB to introduce the basic knowledge about the carbon footprint of construction products, the Scheme, and to provide professional training on Carbon Footprint of Product (CFP) quantification. For further information on the Scheme and the training programmes, please browse the following web link:

零碳天地正籌辦一系列認知培訓課程及專業審計培訓課程，以提供有關本標籤計劃和建築產品碳足跡的基本知識，以及關於產品碳足跡量化的專業培訓。如欲了解更多關於此計劃及培訓課程的資訊，請瀏覽：

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如需查詢，請聯絡：

Dr. Margaret Kam
甘美瑜博士

+852 2100 9831

cls@hkcic.org

CONSTRUCTION INDUSTRY COUNCIL
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CIC INNOVATION AWARD
建造業議會創新獎

Sustainable innovation drives transformation
建 築 創 新 持 續 轉 型

With its commitment to drive for unity and excellence of the construction industry of Hong Kong, the Construction Industry Council (CIC) launched the CIC Innovation Award this year to recognise new technologies and scientific breakthroughs achieved by the academia and construction industry practitioners.

建造業議會致力團結香港建造業以達至精益求精，今年設立「建造業議會創新獎」，旨在表揚在創新技術及科學研究上有傑出成就的學術及建造業界人士。

Awards 獎項	Academia & Industry Practitioners 學術組及業界從業員組	
	Local 本地	International 國際
Grand Prize 創新大獎	HK$300,000	HK$300,000 (~US$37,500)

	Academia 學術組	Industry Practitioners 建造業界從業員組
1st prize 第一名	HK$150,000	HK$150,000
2nd prize 第二名	HK$100,000	HK$100,000
Young Innovator Award 青年創新獎	HK$50,000	HK$50,000

Details are available on
詳情請瀏覽
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(852) 2100 9037 / (852) 2100 9079

(852) 2100 9090

innoaward@hkcic.org

Construction Industry Council

Address : 15/F, Allied Kajima Building,138 Gloucester Road, Wanchai, Hong Kong

Tel : (852) 2100 9000

Fax : (852) 2100 9090

Email : enquiry@hkcic.org

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