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Creating Impacts Through Innovation

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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.

PREFACE

WAI Chi-sing, JP
Permanent Secretary for Development (Works)
Development Bureau

Time flies. I have been working in the Government as an engineer for over thirty years. I have seen many challenging engineering problems landing themselves to interesting and creative solutions during my career. Yet, I expect more to come in the era ahead. One point keeps amusing me is people around always think science, not engineering and technology, as the essence of design process but I beg to differ as it should be the other way round.

Let me take the design of a bridge as an example. In my view, the design of a bridge is a creative process similar to that of a piece of sculpture or music; they are products of creative minds. Engineers will first sketch out the form of the bridge without carrying out vigorous analysis. They have a wide range of structural forms of the bridge at their disposal, be it supported in an arch, beam, suspension or cable-stayed forms. Only when the specific bridge type and geometry is sketched out, it would then be translated into specifications and drawings so that they can be communicated among different disciplines of engineers. The scientific analysis that follows will help refine the structural form that has been selected, determine the building materials to be used and optimise the dimensions of the various structural components. Needless to say, engineers are also required to strike a balance between aesthetic and economic factors during the design and construction process.

It is in this process that I think engineering and technology precede science, at least in the construction industry, and where innovation comes in to integrate the former two areas. History is full of vivid examples that engineering can be advanced even in the absence of a complete understanding of science. Some of these examples are the Great Eastern steam ship in mid-1830s, the Wright Brothers' airplane in 1900s, the Manhattan Project in 1940s and the ARPANET, the precursor of today's Internet, in 1970s. All of these projects were developed and delivered without well-established mathematics and science models behind.

The late Mr. Arthur C. Clarke once said,

"When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong."

With this spirit and on the eve of the inaugural of the iCON, may I wish you all success and a smooth sail to the unchartered territory of the construction technology through development and research which in my view, is a synonym for engineering and science.

The Construction Industry Council (CIC) has been actively striving for unity and excellence of the Hong Kong construction industry since its establishment in 2007. As part of CIC's mission to promote the ongoing development and improvement of the industry, Research and Development (R&D) is of great importance towards enhancing the industry's efficiency and competitiveness. To this end, CIC strongly encourages research activities and the use of innovative techniques that directly meet the industry needs. CIC also promotes the establishment of standards as well as good practices for the construction industry now and into the future.

The CIC invites research proposals from research institutes twice each year. Since September 2012, we have received an overwhelming response of more than a hundred applications in three rounds of invitations. Around HK$17.7 million has been granted to 17 proposed research projects, covering the research areas of concrete and construction technology, productivity, safety, and low carbon technology.

Serving as a link between the academia and the industry, CIC is dedicated to steering research to suit the industry needs as well as promoting innovative research outcomes to applications. One successful example is the "Carbon Labelling Scheme for Construction Products" initiated by the CIC in January 2014, which won the CIOB's Project Innovation Award in 2012 and was acclaimed widely by industry stakeholders on the adoption of low carbon construction materials. The carbon assessment framework and benchmark mechanism of the scheme were originally developed by the research team led by Prof. Thomas Ng of The University of Hong Kong. Analogous innovative ideas and paradigm improvement in the industry are highly treasured. This illustrates that highly treasure innovative ideas which would bring about technical improvement to the industry.

In addition to the carbon labelling scheme, CIC is currently supporting a range of research projects with valuable benefits for the local construction industry. While the academia contributes considerably in research projects, the widespread support from the industry is equally important. With this in mind, CIC publishes this Research Journal "Innovation in Construction" to disseminate the knowledge and innovations generated from research, to inspire further research in construction, and to collect feedback from various industry stakeholders, ensuring that both the academia and the industry are fully informed about the most updated development of the CIC funded research, the advanced techniques available for use, and the pressing problems to be solved.

The publication of "Innovation in Construction" is another step forward in our mission to propagate improvements across the entire industry. I believe the journal will successfully act as a sharing platform among various construction stakeholders by providing the latest research information and the local industry's developments. I hope that readers would find the contents of this journal sufficiently informative, enlightening and meaningful to facilitate collaborative work among each other, and to expedite the development and productivity enhancement of Hong Kong's construction industry.

To this end, I wish to sincerely thank all participants who have contributed to the birth of "Innovation in Construction". With your solid support, I believe this Journal will certainly not only reach the audience in Hong Kong, but also those in other countries of the Asia-Pacific region and the global community at large. Let us work together to engineer our future Hong Kong with innovation and excellence for all to benefit!

LEE Shing-see, *GBS, OBE, JP*
Chairman
Construction Industry Council

CHAIRMAN'S FOREWORD

EXECUTIVE DIRECTOR'S MESSAGE

I am delighted to introduce our Research Journal "Innovation in Construction". Through this inaugural issue, I hope you can see CIC's ambition in promoting research, innovation and development for the Hong Kong construction industry.

To succeed in enhancing and promoting excellence in the Hong Kong construction industry, this Journal publishes high quality research papers with significant novelty and impact in the field of construction, and attempts to enhance the performance and capacity of the entire industry on various prevailing issues related to productivity, advanced technology, quality, project management, computer applications, contractual aspects, occupational safety and health, environmental protection, and sustainable development in the construction industry.

It has been one and a half years since the first launch of our CIC research fund. The six funded research projects awarded in pursuance of the call for funding applications in September 2012 have been smoothly conducted with the financial support and technical assistance from CIC. In this inaugural issue, researchers of these six projects present their update and valuable findings with the view of acquiring constructive feedback from the industry. Prof. Z.L. LI together with his research team reports on the research progress of developing a special type of concrete having both high strength and high elastic modulus for tall buildings. Dr. Square FONG presents the key findings regarding his innovative design of a sustainable trigeneration system for local high-rise commercial buildings. Dr. Y.H. WANG proposes an automatic image collection and analysis system, thereby improving onsite productivity. Prof. S.L. CHAN demonstrates his state-of-the-art design for Hong Kong steel-concrete composite structures. Prof. K.F. CHUNG enlightens us on the progress of the adoption of European Steel Code in the Hong Kong construction industry and the development of the corresponding design guides. Prof. J.N. CAO gives details of s-Helmet, a novel system for improving construction safety based on the real-time localisation technique by automatically issuing an alarm to workers in danger zones.

My appreciation goes to all the researchers of the funded projects who have dedicated themselves in the area of research and development, and have contributed to our Journal. My gratitude also goes to my colleagues at the CIC who have been working hard to make the birth of this journal smooth and successful. The research findings presented in this issue are informative and valuable and I believe they will certainly help enhance the performance of Hong Kong's construction industry. In fact, the research outcomes and innovative techniques could not have been materialised without the strong support from our industry. Please feel free to let us know if you have any comments on our Journal or any feedback regarding research projects in general. "Innovation in Construction" is anticipated to play a significant role in sharing views, ideas and knowledge among various industry stakeholders who care about the industry and society. Only by joining hands would we be in a position to make a big stride forward.

TO Wing, Christopher
Executive Director
Construction Industry Council

EDITORIAL

Jimmy TSE, MH
Chief Editor

Chairman, Task Force on Research
Construction Industry Council

With the intention to facilitate innovation and research for the development of the Hong Kong construction industry, CIC provides research grants to encourage research projects with practical significance to the industry.

Through communication with academia and the industry, CIC realises that it is imperative and timely to provide a knowledge sharing platform where researchers can disseminate their latest findings and thereby acquire constructive feedback and ideas from industry practitioners. “Innovation in Construction” was born for this purpose. Initially, this Journal will be published bi-annually. In this inaugural issue, the carbon labelling scheme for construction products, generated from an 18-month research project is presented. In addition, valuable findings of the six CIC funded research projects are also compiled and revealed.

The Task Force on Research played an essential role in various aspects of the establishment and operations of the CIC research fund. Consisting of top professors, engineers and industry leaders, the Task Force provides professional views and contributes in assessing the research proposals, thus making recommendations, monitoring the progress of the approved projects, and evaluating the outcome and effectiveness of the funded projects. Without their solid support, the CIC research fund could not be operated effectively and efficiently, not to mention the successful publication of this Journal. Appreciation goes to the Task Force members for their efforts and dedication, and they are: Prof. Christopher LEUNG, Ir Joseph MAK, Ir Derrick PANG, Sr James PONG and Prof. S C WONG.

It has been a year and a half since the inception of the CIC research fund, from setting up of the research grant, to the birth of this Journal, during which we have experienced joyful success as well as challenges. CIC and the whole industry never ceases in promoting innovation and research development for the Hong Kong construction industry. “Innovation in Construction (iCon)” shows our past effort, disseminates our current progress, and will witness our future achievements in constructing Hong Kong with innovation and excellence.

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 - Carbon Labelling for Construction Products

Exclusive Interview with an Industry Visionary - Ir Conrad WONG, BBS, JP, Vice Chairman, Yau Lee Holdings Limited

Constructing a Low Carbon Future

The World's First Carbon Labelling Scheme for Construction Products

Ir Conrad Wong is the Chairman of the Hong Kong Green Building Council (HKGBC) and the Past Chairman of the Committee on Environment and Technology (Com-ENT) of the Construction Industry Council (CIC). He also led the Task Force on Carbon Labelling Standard for Construction Materials under the Com-ENT. Ir Wong is dedicated in leading the industry towards greener practices. He was invited to share CIC's journey of developing the world's first carbon labelling scheme for construction products and to offer his perspective on the future of low-carbon construction in Hong Kong.

Inspired by the Needs of the Industry

"How could we source environmental-friendly glass products? Can an authority differentiate 'low carbon' materials from others in the market?" These are two simple, yet profound and challenging questions raised by an industry practitioner during a consultation forum held by the Council for Sustainable Development in 2009. As a representative of the CIC and the Hong Kong Construction Association (HKCA) at the forum, Ir Conrad Wong was inspired by these questions. "At that moment, I was convinced that there was a need for low carbon construction materials in the industry", Ir Wong recalled the story behind the development of the CIC Carbon Labelling Scheme. Building on the momentum from increasing market demand for low-carbon materials as well as the HKSAR Government's carbon reduction target, Ir Wong believed it was timely and vital for construction stakeholders to come together and establish Hong Kong as a low carbon city.

After attending an international conference, Ir Wong noted that "overseas construction experts have already started putting forward carbon tendering, thereby incorporating the carbon footprints of buildings into the tender evaluation in addition to conventional criteria such as cost and quality." Carbon trading was also taking place in countries that signed up for the 1997 Kyoto Protocol (effective in 2005). Ir Wong insisted that "in pursuit of low carbon construction, the fundamental issue of how to assess the carbon footprint of construction products must be addressed." Speaking on the absence of an assessment framework for measuring carbon footprint of construction materials, he elaborated that, "you cannot manage what you do not measure, not to mention making improvements."

Looking forward to the upcoming development of a labelling framework for assessing the carbon footprint of construction materials to be used in Hong Kong, Ir Wong explained that, "the embodied carbon of construction materials involves enormous emissions from transportation and manufacturing processes, which largely depends on the energy consumption and its mix." According to Ir Wong, "direct adoption of overseas carbon inventory is simply inappropriate and impractical." He went on to explain, "Back in 2009, there was no unanimous definition for 'low carbon' materials, nor was there any agreed method for evaluating the carbon footprint of construction materials. The University of Hong Kong (HKU) was therefore engaged by the CIC to develop a Hong Kong-based carbon labelling framework for quantifying and benchmarking the carbon footprints of the construction materials commonly used in our industry, and this was how the CIC Carbon Labelling Scheme was born."

Join Forces to Deliver Transformation

One of the current challenges in initiating the carbon labelling scheme in the industry as identified by Ir Wong is advocating the merits of pursuing low carbon materials. "From a contractor's perspective, cost and quality are still the primary factors to a purchase decision in the industry." To address this, Ir Wong believes that incentives should be offered to client bodies to stimulate demand for low carbon materials, thereby driving innovative low carbon solutions from material suppliers. On this aspect, Ir Wong expected that the labelling scheme will be integrated with the BEAM Plus scheme for a more comprehensive environmental assessment of buildings to further drive the industry towards low carbon construction. In addition, he suggested that public bodies and industry leaders could take the initiative to use labelled low carbon materials so that swift and effective progress can be achieved.

While acknowledging the importance of a driving force from the upstream supply chain, Ir Wong was also aware that material suppliers have an equally important role to play in achieving low carbon construction. From the perspective of material suppliers, Ir Wong admitted that applying for the carbon label requires an environmental investment, which involves carbon auditing and verification, as well as implementing carbon mitigation measures. However, he pointed out that initiating a carbon reduction programme through carbon auditing and labelling can also bring a range of benefits to material suppliers

"In pursuit of low carbon construction, the fundamental issue of how to assess the carbon footprint of construction products must be addressed."

"It is now the right time to reach out and make our Scheme international and popular in Asia!"

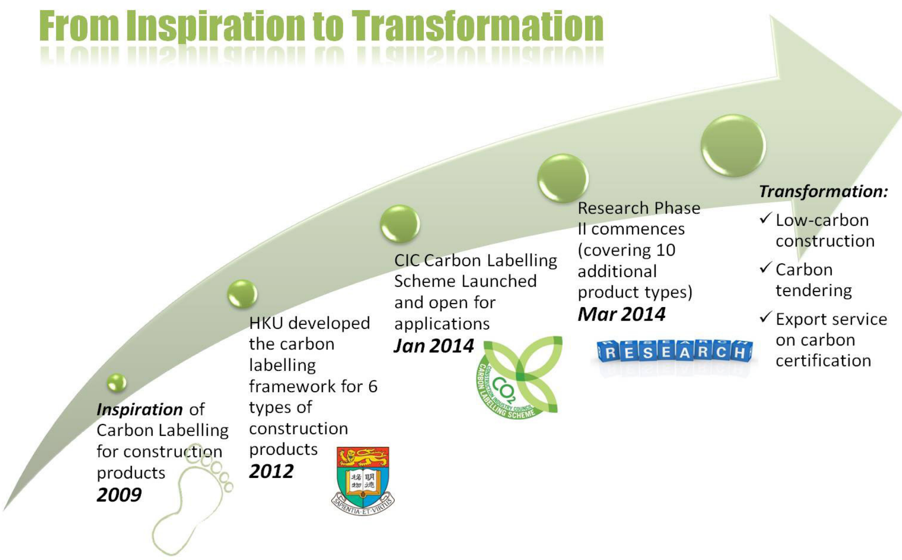
such as cost savings (through minimising energy usage and waste) as well as enhanced competitiveness and building a more positive corporate image. Ir Wong stressed that "this message needs to be conveyed clearly and effectively to the manufacturers."

A New Era of Low Carbon Construction

Looking into the future prospects of the carbon labelling scheme, Ir Wong said he expects growing recognition of the urgency for carbon reductions along the supply chain and that "industry stakeholders will be driven by the Scheme to understand the carbon footprint concept and its relevance to our industry". These stakeholders will then "realise the importance of using low carbon products in project development." Ir Wong stressed, "through incentives, manufacturers will be stimulated to reduce carbon emissions by improving their manufacturing processes, choosing cleaner energy sources, making greater use of recycled materials, etc."

Looking at longer-term prospects, Ir Wong said with great optimism that he looks forward to a new era of low carbon construction through carbon tendering and trading. He also anticipated carbon capture and conversion into bio-fuels to be a continual trend. He highlighted that "methanol is emerging as a viable alternative for reducing the amounts of industrial CO_2 produced". When carbon becomes a tradable commodity, Ir Wong said he predicts the industry will be inclined to trace and reduce their emissions. Regarding the low carbon future of Hong Kong, Ir Wong expressed his sincere hope that Hong Kong can serve as a certification hub for low carbon construction products in Southeast Asia. He passionately feels that Hong Kong has the potential to "export our certification services" and that it is now the right time "for the CIC to reach out and make our Scheme international and popular in Asia!"

From the concept of low carbon construction to the formal launch of the Carbon Labelling Scheme, Ir Conrad Wong witnessed the entire journey of the Scheme's development. His insights and forward-looking views provide us with future directions and inspiration for both the Scheme itself as well as the broader theme of sustainable construction. Though the Scheme is still at an infancy stage, it is expected that it will drive the industry towards building a more profound understanding of carbon footprint, and to facilitate low carbon construction and innovation. In line with Ir Wong's vision, the CIC is committed to developing Hong Kong into a low-carbon city and a benchmark for the region.



Implementation Plan & Future Development

A Green Revolution in Construction

REDUCING EMBODIED CARBON OF CONSTRUCTION FACILITIES THROUGH PRODUCT-BASED CARBON LABELLING SCHEME

S. Thomas Ng[1,*], Julian C.F. Lee[2] and James M.W. Wong[2]

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Carbon embodied in a construction facility is an important but much neglected topic. In the absence of an agreed framework to assess carbon emissions of construction materials at the product level, it is difficult to estimate the embodied carbon accurately. The Construction Industry Council (CIC) in Hong Kong initiated research into a carbon labelling scheme for construction materials by working in collaboration with academia from The University of Hong Kong. The result of this collaborative approach was the framework for the world's first product-based carbon labelling scheme for construction materials.

Keywords: carbon labelling, carbon footprint of product, construction material, embodied carbon.

INTRODUCTION

Minimising the carbon emissions of infrastructure and construction facilities has attracted the serious attention of practitioners and researchers in recent years as the extent of carbon emitted by the construction industry has surpassed many other sectors (González and Navarro, 2006). Analysts generally believe that the construction of more facilities is inevitable to cope with population growth, increasing urbanisation and the demand for better living standards. The problem is aggravated by a huge stock of existing buildings which are less energy efficient than desired. Consequently, any measures to reduce the life cycle carbon footprint of construction facilities would contribute to emission reduction and thus help combat climate change.

Until now, many policies and innovative ideas have focused on the energy performance during the operation phase of a construction facility (Dias and Pooliyadda, 2004). Practical measures include an improvement in energy efficiency from the demand side, for instance by introducing efficient building services equipment, improving the thermal insulation and changing users' behaviour or the adoption of a higher proportion of clean energy from the supply perspective. In order to gauge the environmental performance of a building, various building environmental assessment models including the Hong Kong Building Environmental Assessment Model (BEAM-Plus) and the Leadership in Energy and Environmental Design (LEED) have gained popularity. Despite their robustness and comprehensiveness, these building environmental assessment models put much emphasis on the energy consumption of a building.

Addressing the energy consumption and operational emissions is no doubt essential, but one should not lose sight of the carbon embodied in a facility (Monahan and Powell, 2011) as it is virtually impossible to eliminate the embodied carbon once the construction is completed. Nonetheless, little attention has been attributed to reducing the carbon footprint of a construction project through the careful selection of materials (Brenton et al., 2008). Of various challenges, a lack of reliable carbon footprint data pertinent to construction materials could hinder the use of low carbon materials. Established carbon inventories such as the Inventory of Carbon and Energy initiated by the University of Bath can only provide typical carbon footprint figures of construction materials, and those norms can be influenced by various circumstances like the energy mix of a country. A more reliable approach is by systematically assessing the carbon footprint of a specific construction material at the product level.

The release of the latest standard on product-based carbon footprint accounting, ISO/TS 14067:2013 "Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification and Communication" should help ensure the life cycle carbon emissions of a construction product is accurately measured and represented. With a firm belief that an easy to understand mechanism to account for and disclose the carbon footprint of construction materials can help reduce the overall carbon emissions of a facility, the Construction Industry Council (CIC) in Hong Kong initiated a project to develop a carbon labelling scheme for the construction industry. Having undergone a thorough investigation, the CIC carbon labelling scheme for construction materials was launched in the last quarter of 2013. This paper

*tstng@hku.hk | Prof. S. Thomas Ng

reports the research methodology and findings as well as the latest development of the CIC carbon labelling scheme. The future prospects of carbon reduction in construction through the use of the carbon labelling scheme will also be highlighted.

RESEARCH METHODS

With a desire to develop a carbon labelling scheme for construction materials which is in line with international best practices in general and relevant to the local context specifically, a rigorous research study was conducted by a team of researchers at The University of Hong Kong to (i) examine the implications of a carbon labelling scheme in the construction industry; (ii) unveil the characteristics of different categories of construction materials and their effects on carbon labelling; (iii) develop a framework for auditing the carbon footprint of different construction materials; (iv) establish a mechanism to benchmark the carbon footprint of construction materials to determine the label grading; and (v) formulate strategies and measures to implement a carbon labelling scheme for construction materials.

The research commenced with an extensive desktop study to examine the relevant documents and international standards on greenhouse gas (GHG) assessment frameworks at the product level not least the ISO/TS 14067:2013 guideline. Existing carbon labelling schemes and carbon inventories around the world were also delineated to unveil their scope, assessment principles, benchmarking mechanisms, and verification methods. The information collected provided a solid foundation for the establishment of an initial carbon labelling framework.

Since the introduction of a carbon labelling scheme is new to the construction industry and the implications of these mechanisms to this sector remain largely unexplored, a series of semi-structured interviews were conducted with industry practitioners from government, developers, non-government organisations, consultants, contractors and material suppliers. The interviews served to uncover the potential implications of the proposed carbon labelling scheme, the envisaged elements leading to the success of the carbon label for construction materials, and the strategies for implementing such a scheme in the construction industry.

The research was followed by establishing a classification regime for construction materials to facilitate benchmarking in the subsequent stages. With a clear definition of product categories, process maps portraying the life cycle production process of the three selected construction materials were compiled based on the literature and interview findings. The emission sources associated with each of the production process, such as the fuel consumption, chemical reaction, and fugitive gas, could then be drawn up and presented to the experts and manufacturers for validation. A computer tool was then devised to allow material suppliers to input the necessary emission data for carbon auditing and reporting purposes. To facilitate comparison, a benchmarking mechanism was formulated by making reference to other established eco-labelling schemes and a grading regime was also proposed. These allowed for the design of the world's first product-based carbon labelling scheme for construction materials.

To formulate a series of strategies and measures to implement the carbon labelling scheme in the construction industry, senior practitioners from the industry were consulted to gather some initial insights. Then, a forum involving three carbon labelling experts and more than 70 participants from various sectors within the construction industry was held to share their views on how to effectively put the carbon labelling scheme into practice. More importantly, the detailed procedures for auditing and certification were derived after consulting the accreditation bodies and the industry.

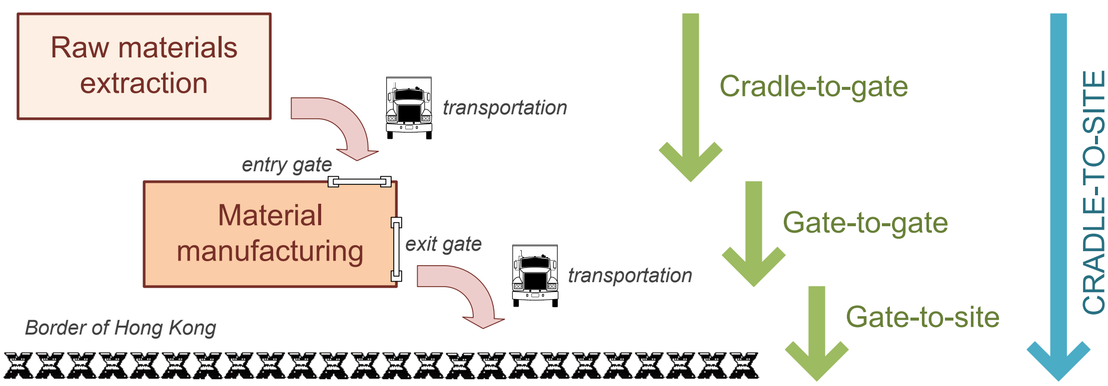

Figure 1 A Cradle-to-Site System Boundary

SYSTEM BOUNDARY

Of the various stages, defining the boundary for carbon footprint assessment was the first and foremost important step as the subsequent calculations would have to include all emissions within the system boundary that have the potential of making significant contribution to the carbon emissions of a product. The system boundary for estimating the life cycle carbon emissions of the selected materials was defined in accordance with ISO 14025:2006 "Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures". For the three selected materials - cement, reinforcing bar and structural steel - the system boundary was set as cradle-to-site as shown in Figure 1.

Despite the completeness of a cradle-to-grave system boundary, the different life span of materials when used in various project types such as infrastructure facilities or building schemes renders it impossible to accurately assess the carbon footprint arising from the use phase. More importantly, as the material property may affect the energy performance of a building, the energy at the operational phase should be evaluated by the building environmental assessment models like BEAM-Plus and LEED instead. Considering construction material's operational emissions during product-based carbon auditing may, therefore, lead to double counting. As for the emissions caused by site operations and demolition, they are not only relatively trivial but could also be affected by the choice of construction or demolition methods and equipment. As a result, the site and demolition emissions are also excluded.

The carbon footprint of a product is taken as the carbon emitted during raw material extraction and the manufacturing process up to the point when the finished construction material is delivered to the border of Hong Kong. The assessment shall include, but not be limited to, energy use, combustion processes, chemical reactions, loss to atmosphere of refrigerants and other fugitive GHGs, process operations, service provision and delivery, land use and land use change, and waste management.

CARBON FOOTPRINT OF A CEMENT PRODUCT

Portland cement is used as an example to further illustrate the mechanism of how the carbon footprint of a product is assessed. Cement is extensively used in the construction industry as an essential ingredient in producing concrete. As the production of cement is energy intensive, consuming large quantities of fuel during manufacturing, especially the kilning process, the cement industry alone generates approximately 5% of the global anthropogenic carbon emissions (IPCC, 2001).

A manufacturer shall calculate the potential contribution of a particular Portland cement product to global warming expressed as carbon dioxide equivalent (CO_2e) by quantifying all significant GHG emissions and removals over the cement product's life cycle. Carbon emitted from cement production can be divided into three key process categories namely upstream, core and downstream. Table 1 illustrates the sub-processes involved in cement production according the three key processes.

The carbon footprint assessment framework was developed based on the "CO_2 and Energy Accounting and Reporting Standard for the Cement Industry" released by the World Business Council for Sustainable Development (2011).

Table 1 Carbon Emitted during Different Stages of Production of Portland Cement

System Boundaries	Processes
I. Upstream Processes	○ Extraction and production of raw material used in the production and packaging of the finished product ○ Transportation of raw material to the plant ○ If relevant, recycling process of recycled materials used in the product ○ The production process of energy wares used in raw material production
II. Core Processes	○ Production of raw mix ○ Burning of clinker ○ Grinding of cement ○ Storage of cement for dispatch
III. Downstream Process	○ Transportation from manufacturing to site

II. CO2e EMISSIONS								
A. Direct CO2e Emissions								
A1. CO2 from Raw Materials Calcination and Combustion			Product 1	Product 2	Product 3	Product 4	Product 5	Total
19	Calcination emission factor, corrected for CaO- and MgO imports	[kg CO2/ t cli]	525	525	525	525	525	525
20	Organic carbon content of raw meal (average)	[%, dry weight]	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
21	Raw meal : clinker ratio	[--, dry weight]	1.55	1.55	1.55	1.55	1.55	1.55
22	Raw meal consumption	[t/yr, dry weight]						
23 a	CO2 from calcination of raw materials for clinker production	[t CO2/yr]						
23 b	CO2 from calcination of bypass dust leaving the kiln system	[t CO2/yr]						
23 c	CO2 from calcination of CKD leaving the kiln system	[t CO2/yr]						
23 d	CO2 from combustion of organic carbon content of raw meal	[t CO2/yr]						
23	Total CO2 from raw materials calcination and combustion	[t CO2/yr]						
A2. CO2e from Kiln Fuels			Product 1	Product 2	Product 3	Product 4	Product 5	Total
24 a	CO2e from conventional fossil fuels	[t CO2e/yr]						
24 b	CO2e from alternative fossil fuels	[t CO2e/yr]						
24 c	CO2e from biomass / biofuels	[t CO2e/yr]						
24	Total CO2e from kiln fuels	[t CO2e/yr]						
A3. CO2e from Non-Kiln Fuels			Product 1	Product 2	Product 3	Product 4	Product 5	Total
25 a	CO2e from quarrying / mining raw materials	[t CO2e/yr]						
25 b	CO2e from on-site transportation	[t CO2e/yr]						
25 c	CO2e from equipment	[t CO2e/yr]						
25 d	CO2e from room heating / cooling	[t CO2e/yr]						
25 e	CO2e from on-site power generation	[t CO2e/yr]						
25	Total CO2e from non-kiln fuels	[t CO2e/yr]						
Total Direct CO2e Emissions			Product 1	Product 2	Product 3	Product 4	Product 5	Total
26	Total direct CO2e: all sources	[t CO2e/yr]						

Figure 2 Computer Tool for Capturing and Assessing the Carbon Footprint of Cement

The assessment should consist of direct emissions arising from raw material calcinations and combustion, combustion of kiln fuels, and combustion of non-kiln fuels. Any combustion of kiln fuels as well as those fuels used for drying and processing the raw materials should be taken into account. The combustion of non-kiln fuels which are not covered in the definition of kiln fuels, such as for quarrying or mining of raw materials, on-site transportation, or room heating, should also be accounted for. Apart from direct emissions, indirect GHG emissions including external production of electricity consumed by cement manufacturers, production of bought raw materials and clinker, third-party transportation and land use change should also be reported. The details can be found in the relevant assessment guidelines developed by the CIC.

A computer tool was developed to guide and assist manufacturers identifying and inputting the necessary data for carbon accounting and auditing. As shown in Figure 2, the tool provides different templates for manufacturers to input the emission data by making reference to different products they produce. Based upon the system input and output data as well as the built in information such as the conversion factors for different types of fuels, the computer tool computes the total carbon footprint of the product automatically based on a functional unit of tonne of CO_2e per tonne of Portland cement produced.

As the first product-based carbon footprint assessment framework, its robustness, coverage, and user-friendliness must be carefully evaluated. The validation first took the form of face-to-face interviews with relevant product manufacturers. At the interviews, the process map, system boundary and computer tool were presented. Valuable feedbacks was solicited which helped improve the assessment framework. Wider consultation was then conducted through a forum. At the forum construction professionals and carbon auditors expressed their views on how to further increase the accuracy of assessment especially when there is an absence of some first-hand information along the supply chain or production process. Based on their suggestions, relevant norms and supplementary information as identified from international guidelines and literature were incorporated into the computer model to cater for missing data.

A GLIMPSE OF THE CIC CARBON LABELLING SCHEME

The carbon footprint of a product once audited and reported by a certified carbon auditor and validated and verified by a GHG validation verification body may result in the issuance of a carbon label (Figure 3) by the scheme holder. The most important information on the carbon label is the carbon rating. To help differentiate the market leaders, the carbon ratings are divided into five categories ranging from 'outstanding', 'very good', 'good', 'fair' to 'improvement needed' by benchmarking against the emissions of the same category of construction material(s). By simply making reference to the assigned carbon rating, clients, design team members and contractors can easily distinguish which is a low carbon material and thus help support decision making.

In addition to the carbon rating, further information is incorporated in the carbon label and this includes the details of the product which the carbon label refers to such as the name of product, size, weight, assessment boundary, and country of origin; the carbon footprint of the product at different key life cycle stages; and the

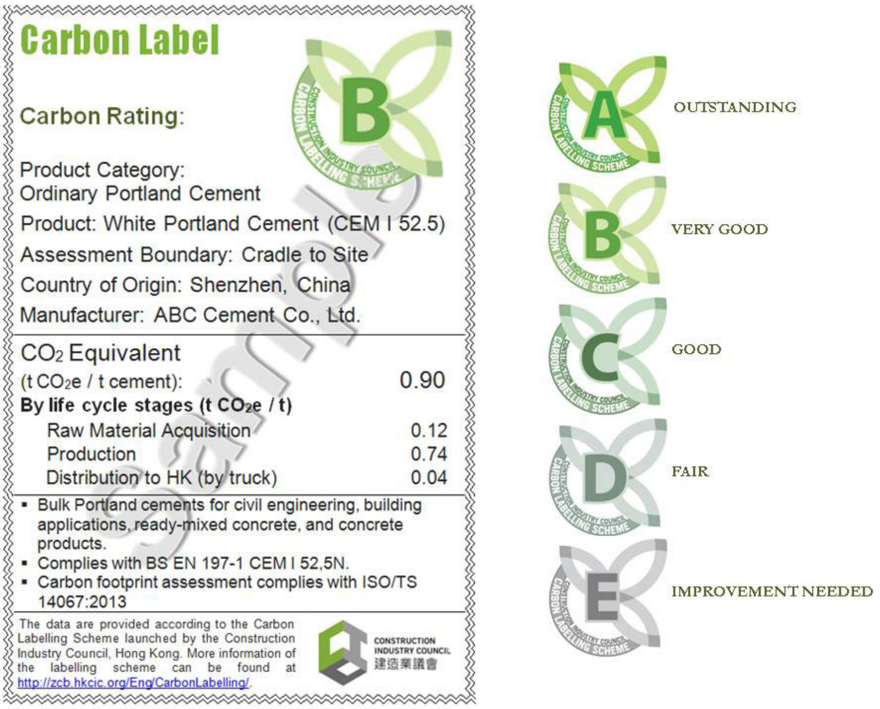

Figure 3 The Construction Industry Council's Carbon Labelling Scheme for Construction Material

detailed information of the carbon label such as the assessment method and the details of the scheme holder. The manufacturer will be granted a licence to display the carbon label on their product and communicate with the other stakeholders regarding the carbon footprint of the product they produce.

IMPLICATIONS OF CARBON LABELLING

Given that the manufacturing of construction materials alone could contribute to as much as 70% of carbon emissions at the construction stage (Smith et al., 2002), it is desirable to reduce the carbon emitted from the construction sector through prudent selection of low carbon materials. The carbon labelling scheme described in this paper provides a fair and transparent mechanism for appraising the carbon footprint at product level.

However, as with any other green initiatives, successful implementation of the carbon labelling scheme for construction materials depends on the support of different industry stakeholders (Ng et al., 2011). Not only do we need a strong push from policy and decision makers, a pulling force from manufacturers and suppliers will also be indispensable.

From the client's perspective, specifying the use of low carbon materials (those that have achieved a certain carbon rating) in a construction project or requiring disclosure of the carbon rating or carbon footprint of major construction materials would encourage the design team and contractor to source the labelled low carbon materials.

As for material manufacturers and suppliers, they should realise the benefits brought by carbon auditing especially in terms of identifying the major energy sources and thus introduce pragmatic solutions to cut down on fuel or electricity consumption. This would not only result in cost savings, but should also help raise the company and product image through carbon reduction and promote better corporate social responsibility.

The CIC is actively liaising with the BEAM Society to explore the potential of integrating the CIC carbon labelling scheme with BEAM-Plus so as to provide an even more comprehensive life cycle environmental assessment for buildings. The integration with BEAM-Plus should certainly provide a strong incentive for clients and design team members to reduce the embodied carbon of their construction facilities.

CONCLUSIONS

The problem of global warming is exacerbating. Since the construction industry consumes large quantities of materials which are carbon intensive to produce, taking effective measures to reduce carbon emissions in construction is absolutely imperative. The CIC carbon labelling scheme is designed to provide a common basis for carbon emissions quantification and comparison within a product category. Such a labelling scheme will inform and enable meaningful carbon emission reduction programmes.

The proposed carbon assessment frameworks for cement, reinforcing bar and structural steel are developed in accordance with ISO/TS 14067:2013 "Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification and Communication" and ISO 14025:2006 "Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures". Any material manufacturers who are interested to apply for the carbon label should comply with all the general requirements and methods stated in ISO/TS 14067:2013 for assessing the life cycle carbon emissions of their products under the proposed labelling scheme. The assessment framework described in this paper serves to provide specific requirements according to the production process of various construction materials as well as that stipulated in ISO/TS 14067:2013. The carbon labelling scheme should, therefore, be in-line with international best practices. With suitable adaption, the carbon footprint assessment framework described in this paper should be equally applicable to other countries.

While the CIC in Hong Kong is planning to start launching the carbon labelling scheme with three product categories - cement, reinforcing bar and structural steel - a series of awareness training and auditor training courses is being organised to equip various stakeholders. The next phase of research which focuses on another 10 commonly used materials in the construction industry is already underway. It is envisaged that the CIC carbon labelling scheme will gain popularity over time as more and more clients begin to specify the use of labelled low carbon materials and when manufacturers are aware of the tangible and intangible benefits of carbon labelling. The CIC carbon labelling scheme showcases the determination of Hong Kong's construction industry in achieving the goal of mission of emission reduction.

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BIOGRAPHY

Thomas Ng is a Professor in the Department of Civil Engineering, The University of Hong Kong and the Executive Director of the Centre for Infrastructure and Construction Industry Development at the same university. Over the years, Professor Ng has secured more than HK$52 million of research grants and published over 300 scholarly items. His recent research interests include carbon footprint of construction products, life cycle assessment, construction industry development and performance, project delivery systems, contractor selection and construction information technology.

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LOCAL CARBON INVENTORY DATABASE FOR CONSTRUCTION MATERIALS: APPROACHES AND POTENTIAL IMPACTS

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According to World Wild Fund (WWF), the construction sector was reported to be the second largest contributor to Hong Kong carbon footprint and around 85% of its carbon footprint was embodied in imported goods and services from upstream material inputs to Hong Kong. Therefore, it is crucial to study the embodied carbon of construction materials and select the low carbon materials in order to achieve a low carbon built environment. This project aims to develop a local embodied carbon database, namely ECO-CM (Embodied Carbon Of Construction Material), for the commonly used construction materials in Hong Kong. The life cycle assessment approach used in the development of the ECO-CM database is presented and illustrated in this paper. As embodied carbon values are regional specific, primary data were collected from the material suppliers through questionnaires for the carbon footprint calculation. A "Cradle-to-Site" system boundary was used in the ECO-CM database to improve the accuracy and completeness of the results. It is expected that the completed ECO-CM database can provide a basis for selection of green materials, development of carbon labels, and estimation of building facility carbon footprint, thereby helping to construct a low carbon Hong Kong.

Keywords: cradle-to-site, database of embodied carbon, green construction materials, life cycle assessment.

INTRODUCTION

Construction activities consume a large quantity of mineral resources and fossil energy, resulting in the release of airborne emissions to the atmosphere. According to the Hong Kong Ecological Footprint Report 2010 released by WWF, four million tons of carbon dioxide was emitted in Hong Kong and the construction sector was reported to be the second largest contributor to the Hong Kong carbon footprint in 2007 (Cornish et al., 2011). Of the carbon footprint associated with the construction sector, around 85% was embodied carbon in imported goods (i.e., construction materials) and services, from upstream material inputs to Hong Kong. Therefore, the reduction of embodied carbon in the imported construction materials will lead to a significant decrease of overall carbon footprint.

The embodied carbon of a construction material has been defined as the total carbon released over its life cycle, which would include at least raw material extraction, product manufacturing and transportation (Hammond and Jones, 2008). There have been various studies on the embodied carbon of materials in the past years. Table 1 summarises the life cycle carbon inventory databases in different countries and regions, which include the Ecoinvent developed by the Swiss Centre for Life Cycle Inventories, the European reference Life Cycle Database (ELCD) by the European Union, the Inventory of Carbon and Energy (ICE) by University of Bath, and the Chinese reference Life Cycle Database (CLCD) by Sichuan University. These databases evaluate the direct and indirect impacts of the material manufacturing processes using life cycle assessment technique. However, since the manufacturing process, fuel mix and raw material sources may be different in various regions and countries, the values of embodied carbon are region-specific. Therefore, the life cycle carbon inventory databases in other regions cannot be used directly for Hong Kong and hence a local database needs to be developed.

This project aims to develop a local embodied carbon inventory database for Hong Kong construction materials, namely Embodied Carbon Of Construction Materials (ECO-CM). This database will cover the major construction materials that are commonly used in Hong Kong. In order to obtain the embodied carbon, an accounting approach was developed to calculate greenhouse gas (GHG) emissions (e.g., CO_2, CH_4 and N_2O) over the material life cycle. The data used for the calculation are collected from

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Table 1 Life Cycle Carbon Inventories of Construction Materials in Different Regions

Region	Name of the Database	Developer	System Boundary
Switzerland	Ecoinvent	Swiss Centre for Life Cycle Inventories	Gate-to-Gate
Europe	ELCD (European reference Life Cycle Database)	European Union	Cradle-to-Gate
United Kingdom	ICE (Inventory of Carbon and Energy)	University of Bath, UK	Cradle-to-Gate
China	CLCD (Chinese reference Life Cycle Database)	Sichuan University, China	Cradle-to-Gate
Hong Kong	Embodied Carbon Of Construction Materials (ECO-CM)	The Hong Kong University of Science and Technology (HKUST) (under development)	Cradle-to-Site; Cradle-to-Gate

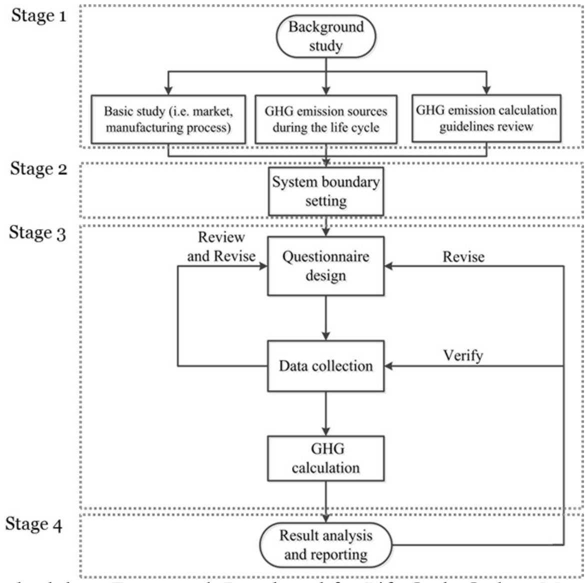

Figure 1 Methodology Framework Developed for Life Cycle Carbon Measurement

manufacturers via questionnaire surveys and face-to-face interviews with stakeholders. The content of this paper is organised as follows: Section 2 describes the approach used to create the embodied carbon database. Section 3 provides an example of Portland cement to illustrate how embodied carbon is calculated using the developed approach. Section 4 discusses the potential impacts of the ECO-CM database. Section 5 concludes the whole paper.

APPROACHES

Life Cycle Assessment (LCA) is a holistic methodology to evaluate the potential environmental impacts over the life cycle of a product. The LCA approach used in this study has been developed with reference to international standard guidelines ISO 14040:2006, ISO 14044:2006, Publicly Available Specification (PAS) 2050:2008 (defra 2008), and ISO/TS 14067:2013. As shown in Figure 1, the approach consists of four main stages: (1) background study, (2) system boundary setting, (3) data collection and calculation, and (4) result analysis and reporting.

Background Study

The purpose of background study is to ascertain the main features of a material including the characteristics, classification, manufacturing process and product market share. Literature review for material classification refers to international and regional specifications (e.g. ISO, The American Society for Testing and Materials (ASTM)) and existing databases such as ICE and Ecoinvent. Material classification differentiates the materials into those for construction purpose and for non-construction purposes. Following the material classification, market share information for the construction materials will be collected and the manufacturing process will be investigated. Finally, with respect to the material manufacturing process, the GHG emission sources are identified stage by stage from raw material extraction to transport of finished products.

System Boundary Setting

System boundary setting determines the scope of a LCA study. As shown in Figure 2, the material system is divided into a series of unit stages including raw material acquisition, product manufacturing, transportation of finished product, product use on construction sites, and end-of-life treatment and recycling. System boundary setting should separate a number of unit stages of a construction material system from externalities. The unit stages covered in the system boundary are the focus of the subsequent calculation.

A system boundary over the full product life cycle can be "Cradle-to-Grave", "Cradle-to-Cradle", "Cradle-to-Site", "Cradle-to-Gate" and "Gate-to-Gate". "Cradle-to-Grave" system boundary includes all five stages from raw material acquisition ("cradle") to end-of-life treatment and disposal ("grave"). "Cradle-to-Cradle" is a special kind of "Cradle-to-Grave" assessment, in which product is recycled at the end-of-life stage and becomes the cradle of another product life cycle. "Cradle-to-Gate" is an assessment of partial product life cycle from raw material acquisition ("cradle") to the factory exit gate ("gate") before the product is transported to market. "Gate-to-Gate" system boundary includes only the product manufacturing process from the factory entry gate ("gate") to the factory exit gate ("gate"). In the ECO-CM database, calculation of material embodied carbon is examined over the "Cradle-to-Site" life cycle, which covers a partial product life cycle from resource extraction ("cradle") until the product has reached the point of use (i.e., the border of Hong Kong). Product transportation is considered in ECO-CM because most of the construction materials used in Hong Kong are produced by overseas manufacturers and consideration of emissions from product transportation could improve the accuracy and completeness of the result. On the other hand, product use and disposal phase are not considered because the emissions from which are difficult to predict with uncertainties.

Data Collection and Calculation

Data collection and calculation involve recording/ collecting, quantifying and auditing the relevant GHG emissions of a material system over the "Cradle-to-Site" life cycle. The data used to calculate the embodied carbon are collected from material suppliers through questionnaire surveys. The questionnaire contains eight parts - (1) company information, (2) product types and market share, (3) raw material types and consumption, (4) raw material transport, (5) electricity consumption, (6) fuel combustion, (7) emissions from industrial processes, and (8) finished material transport. These questions aim to collect the information on raw materials and energy consumption in the production of a construction material. The part on emissions from industrial processes is specific to individual construction materials, such as Portland cement and structural steel. Questionnaires should be carefully designed to incorporate all related GHG emission sources over the material life cycle.

The prepared questionnaires are delivered to a list of material suppliers for data collection. The plant-specific data from material manufacturers are used to calculate the GHG emissions for each construction material. With reference to international guidelines such as IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and the Greenhouse Gas Protocol (WRI and WBCSD, 2011), the emission of each GHG is given as:

$$E_i = Q \times EF_i \quad (1)$$

where i represents the greenhouse gas i, Q refers to the quantity of material consumption, energy consumption or material production, and EF_i refers to the emission

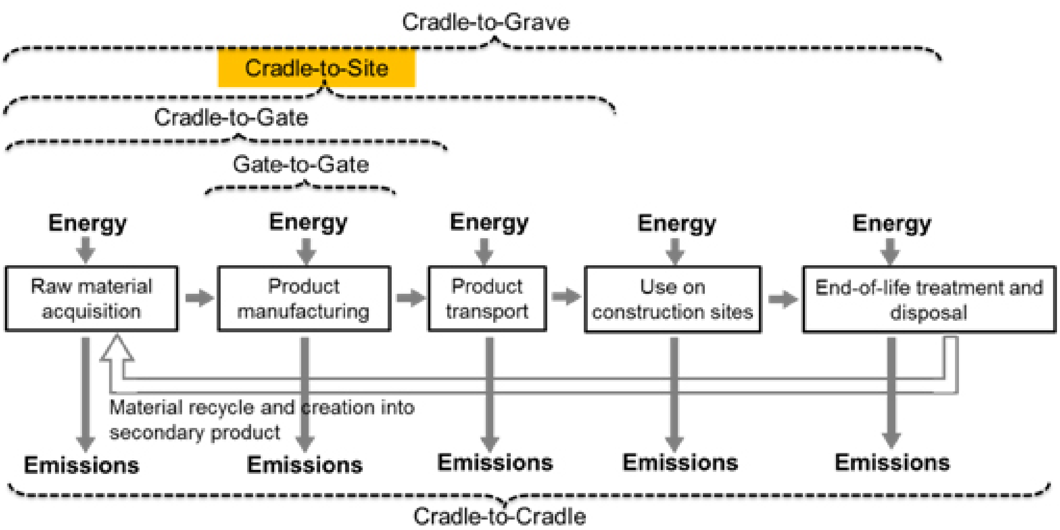

Figure 2 Different Life Cycle Boundaries of a Product System

factor in terms of the greenhouse gas *i*. With reference to IPCC, the six GHGs identified in the Kyoto Protocol are considered in the ECO-CM database. They are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). The GHG emissions are then integrated into the effect of global warming, expressed in terms of kg CO_2 equivalent (CO_2e), as follows:

$$EC = \sum E_i \times GWP_i \qquad (2)$$

where E_i stands for the emission of greenhouse gas *i* and GWP_i represents the global warming potential for that gas. The *GWP*s are 1 for CO_2, 25 for CH_4, and 298 for N_2O respectively (Forster et al., 2007). The result determined from Equation (2) over the "Cradle-to-Site" life cycle is the embodied carbon of a construction material.

Result Analysis and Reporting

The final stage of the approach is to analyse and report the material embodied carbon. Result analysis can increase the environmental knowledge about a construction material and identify opportunities to improve the environmental performance of material at various stages in its life cycle. In real applications, stakeholders can easily identify the stage that emits the largest amount of GHG and take actions to minimise the emissions. Based on the analysis results, the reporting stage could provide key findings and recommendations to improve the material production technologies and process.

ILLUSTRATIVE EXAMPLE OF PORTLAND CEMENT

In this section, Portland cement is selected as an illustrative example to explain how the approach evaluates the embodied carbon of construction materials. Portland cement is the hydraulic binder used to produce concrete and mortar. As the first step, the engineering properties, current market share and manufacturing process of cement were investigated in background study. Figure 3 shows the LCA system boundary for Portland cement. The raw materials, energy inputs and manufacturing processes within the system boundary are the focus of the study.

After background study and system boundary setting, first hand data were collected for GHG calculation and analysis. The accuracy of the GHG emission calculation depends on the availability and quality of the data collected from manufacturers. Therefore, a bilingual questionnaire (English and Traditional Chinese) was carefully designed and sent to the cement manufacturer for the data collection. Based on the data collected and the system boundary defined, the GHG emissions over the "Cradle-to-Site" life cycle can be determined.

In this paper, a cement manufacturer located in Guangdong, China is considered as an illustrative example. The manufacturer produces CEM I - Portland cement and the annual production of clinker and cement are 260,000 tonnes and 300,000 tonnes, respectively. In addition to the produced clinker, the manufacturer also imports 20,000 tonnes of clinker from Vietnam. Except that 124,800 tonnes of limestone are imported from Japan, all other raw materials (i.e. 15,000 tonnes of gypsum, 83,200 tonnes of limestone, 26,000 tonnes of shale, 6,000 tonnes of fly ash and 4,000 tonnes of packaging materials) are obtained from local suppliers in mainland China. The raw materials are transported to the cement factory and grinded to fine powder for calcination. Under a temperature of 1400^{o}C - 1500^{o}C, the limestone which is mainly calcium carbonate ($CaCO_3$) is calcinated, producing lime and CO_2 (IPCC, 2006). During cement manufacturing, around 41,000 tonnes of petroleum coke is combusted in the kiln and 52,500 MWh of electricity is consumed to power the mechanical equipment. Gasoline and biomass are also used to drive the on-site vehicles for transporting the raw materials. The resulting hard substance from calcination is grinded with 5% of gypsum powder to make Portland cement. The finished cement is packaged and transported to the place of use by watercraft (50%) or HGV truck (50%).

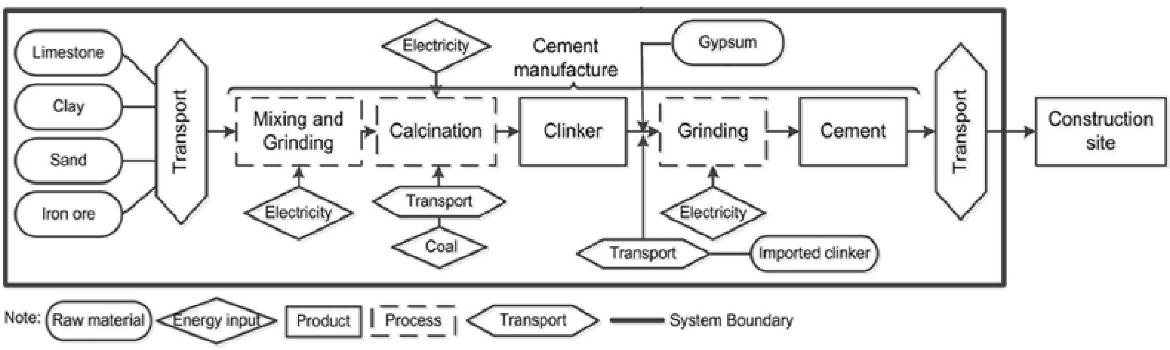

Figure 3 "Cradle-to-Site" System Boundary of Portland Cement

After calculation, revision of the questionnaire and verification of the data were needed for keeping results accuracy and data consistency. Table 2 summarises the "Gate-to-Gate", "Cradle-to-Gate" and "Cradle-to-Site" results of the illustrative example. The total "Cradle-to-Site" GHG emission associated with cement production is 0.8977 kg CO_2e/ kg cement. The manufacturing process ("Gate-to-Gate") emits 0.7298 kg CO_2e/kg cement and accounts for the highest proportion (81.30%) of the total GHG emissions during the cement life cycle. Combustion of petroleum coke is the major contributor, which accounts for 34.42% of emissions. This is followed by calcination (33.96%), electricity consumption (12.92%) and imported clinker (0.01%). The GHG emission due to raw material

Table 2 Results of CO_2e for Each Stage over the Cement Life Cycle

(1) Raw material	**kg CO_2e/kg clinker**	**Percentage**	**kg CO_2e/kg cement**	**Percentage**
Gypsum	N.A.	-	0.00650	-
Limestone (Guangdong)	0.02880	-	0.02496	-
Limestone (Japan)	0.04320	-	0.03744	-
Shale	0.00020	-	0.00017	-
Fly ash	0.00018	-	0.00016	-
Packaging material	0.01985	-	0.01720	-
Imported clinker	N.A.	-	0.05333	-
Petroleum coke	0.01419	-	0.01230	-
Gasoline	0.00001	-	0.00001	-
Total CO_2e (1)	0.10644	11.01%	0.15208	16.94%
(2) Raw material transport	**kg CO_2e/kg clinker**	**Percentage**	**kg CO_2e/kg cement**	**Percentage**
Limestone (Japan)	0.00051	-	0.00044	-
Shale	0.00066	-	0.00058	-
Fly ash	0.00012	-	0.00010	-
Packaging material	0.00013	-	0.00011	-
Imported clinker	0.00447	-	0.00388	-
Petroleum coke	0.00082	-	0.00071	-
Biomass	0.00013	-	0.00011	-
Total CO_2e (2)[a]	0.00686	0.71%	0.00595	0.66%
(3) Cement manufacturing	**kg CO_2e/kg clinker**	**Percentage**	**kg CO_2-e/kg cement**	**Percentage**
Petroleum coke	0.35646	36.87%	0.30894	34.42%
Gasoline	0.00007	0.01%	0.00006	0.01%
Electricity consumption	0.13380	13.84%	0.11596	12.92%
Calcination	0.35177	36.39%	0.30487	33.96%
Total CO_2e (3)	0.84210	87.11%	0.72982	81.30%
(4) Product transport	**kg CO_2e/kg clinker**	**Percentage**	**kg CO_2e/kg cement**	**Percentage**
Cement by watercraft(50%)	0.00192	-	0.00166	-
Cement by HGV truck(50%)	0.00942	-	0.00816	-
Total CO_2e (4)	0.01133	1.17%	0.00982	1.09%
CO_2e (Cradle-to-Gate)	0.95540	98.83%	0.88785	98.91%
CO_2e (Gate-to-Gate)	0.84210	87.11%	0.72982	81.30%
CO_2e (Cradle-to-Site)	0.96674	100.00%	0.89767	100.00%

- a.GHG emissions due to transportation of gypsum, limestone (from Guangdong supplier) and gasoline are very small (≤ 0.00002).
- N.A. refers to not applicable.

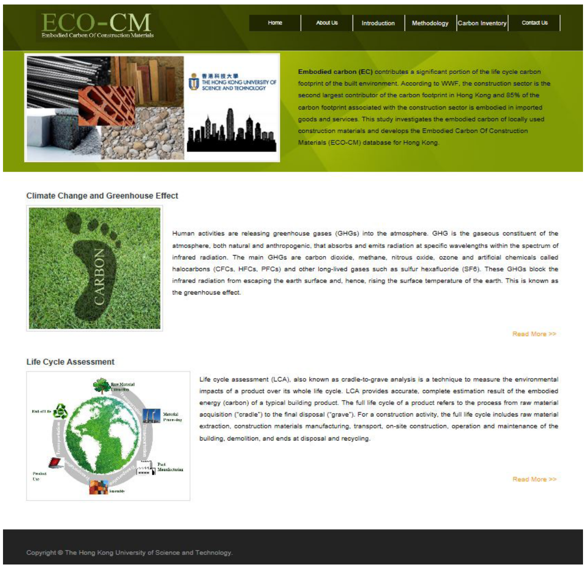

Figure 4 A Snapshot of the ECO-CM Website

production (16.94%) is the second largest contributor to the embodied carbon of cement. The GHG emissions due to raw material transport and product transport, which are 0.66% and 1.09% respectively, are less significant as compared with the manufacturing process. The results of cement can be used to support the environmental performance assessment or identification of improvement potentials in cement manufacturing. For other construction materials involved in this study, the embodied carbon can be calculated following similar procedures described in the cement study.

POTENTIAL IMPACTS

In addition to Portland cement, other construction materials are covered in the development of the ECO-CM database. The approach may be modified and adjusted for other material systems for the calculation if needed. Parts of the results will be available online (as shown in Figure 4; available at http://ihome.ust.hk/~cejcheng/ec/) as a reference for the local construction industry, academia and consultant agencies. The ECO-CM database will fill the gap for assessing the carbon footprint of the built environment in Hong Kong. Specifically the ECO-CM database can provide several benefits to the local construction industry, as follows:

Procurement of low carbon materials

In Hong Kong, there is a trend to consider the utilisation of low carbon materials in the green building evaluation system (i.e., BEAM Plus). The evaluation system encourages contractors to utilise low carbon materials during the building construction stage. Under such circumstances, the ECO-CM database provides a benchmark for evaluation and selection of the low carbon materials for green procurement.

Development of carbon labels

The materials with different embodied carbon values can be classified and assigned with a carbon label to indicate its relative level of carbon emission. The carbon labels could enable a company to differentiate its product from competitors and prompt the development of greener materials. The assessment approach developed in this study could serve as a reference for carbon measurement and auditing in the application of carbon labels. In addition, the values in the ECO-CM database could serve as a benchmark to decide the grade of carbon labels.

Prediction of GHG emissions

The ECO-CM provides a guideline for prediction of GHG emission in material production as well as the GHG emissions embodied in buildings and infrastructures. For example, cement manufacturers can use the "Gate-to-Gate" embodied carbon to estimate the GHG emissions in cement production. For a building project, the "Cradle-to-Site" embodied carbon of each material can be applied to calculate the embodied carbon of a building.

Development of green construction materials

The ECO-CM provides the amount of GHG emitted in different stages during the material life cycle. The information can help identify the stage that incurs serious GHG emissions and find out the optimal solution in reducing its emission. In this way, the impact of global warming can be minimised because the GHG emissions during the material life cycle can be reduced.

In recent years, there are research and industry efforts to design the optimal structures of a building with respect to cost and material usage. With the use of carbon inventories like the ECO-CM database, engineers can estimate the embodied carbon of each component (e.g., concrete and steel) as well as the whole building. People can then use this information to optimise the structural configuration for minimising the embodied carbon of the building and facilitating the design of low-carbon buildings.

CONCLUSIONS

This paper presents the development of a local embodied carbon database for construction materials in Hong Kong, namely ECO-CM. The ECO-CM database is different from the existing carbon inventory databases in two aspects. First, the ECO-CM database considers a "Cradle-to-Site" system boundary from raw material acquisition to the transportation of finished materials to the border of Hong Kong. Second, plant-specific first hand data from material manufacturers and suppliers are collected and used in the calculation. With these two characteristics, ECO-CM provides a more accurate and local specific estimation of the embodied carbon of construction materials.

A methodology approach has been developed and used to create the database. One illustrative example of Portland cement is presented in this paper to show how the approach evaluates the embodied carbon of a construction material. In addition to Portland cement, other materials that are commonly used in construction such as aluminium, concrete, steel and wood products are covered in the ECO-CM database. It is expected that the completed database can benefit the local industry through green material procurement, GHG emission prediction, and green material benchmarking.

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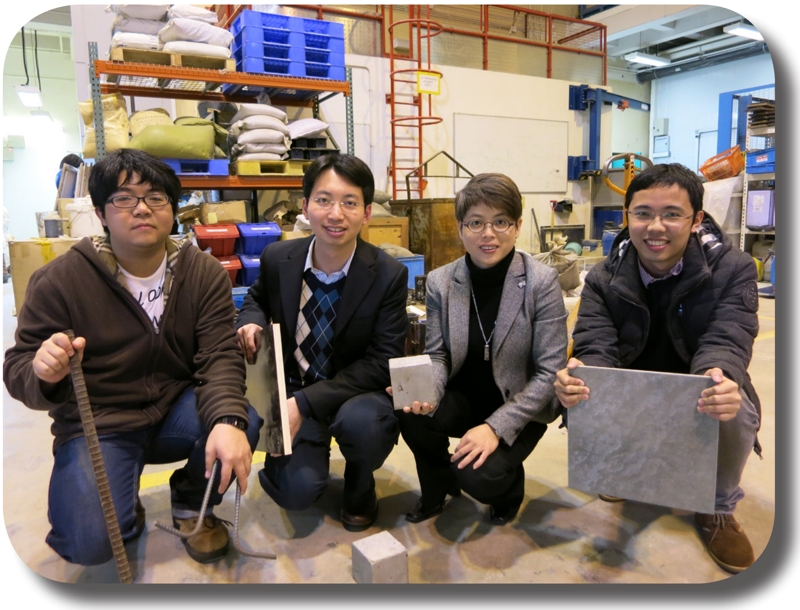

BIOGRAPHY

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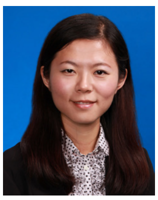
Mr. Vincent Gan is a Ph.D. student in the Department of Civil and Environmental Engineering at HKUST. He was a dual bachelor's degree student in Mainland China and obtained a master degree from HKUST. His current research focuses on life cycle assessment of construction materials, agent-based modeling and simulation, and construction supply chain management.

Mr. Ran Jing is an MPhil student in the Department of Civil and Environmental Engineering at HKUST. He holds a bachelor degree in chemical engineering and a master degree in civil and environmental engineering. His areas of interest are life cycle analysis and energy conservation.



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Research Papers

DEVELOPMENT OF HIGH MODULUS CONCRETE FOR TALL BUILDINGS

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A special type of concrete having both high strength and high elastic modulus was developed, and its properties were characterised. Uniaxial compression test, dynamic and static elastic modulus tests were conducted to measure the mechanical properties of concrete specimens with different types of coarse aggregate, fine aggregate as well as different proportions of sand/coarse aggregate ratio or different replacement ratio of cement by silica fume. The experimental results showed that coarse and fine aggregate had significant effects on elastic modulus of concrete and limited influence on compressive strength. Higher proportion of silica fume led to higher long-term elastic modulus while lower sand ratio did not contribute much to enhancing stiffness. A particular concrete with the compressive strength of 70 MPa and the elastic modulus of 46 GPa was developed for tall buildings.

Keywords: coarse aggregate, elastic modulus, high modulus concrete.

INTRODUCTION

The number of high-rise buildings in Hong Kong is more than any other cities in the world, many of which are widely well known, such as Two International Finance Centre (completed in 2003) and International Commerce Centre (completed in 2010). Concrete is the main construction material for these skyscrapers and makes great contributions to the structural behaviour. Among various mechanical properties of concrete, not only compressive strength but elastic modulus is also significant. However, elastic modulus goes up linearly with square root of compressive strength according to the empirical relationship established in ACI Building Code (1995), indicating that elastic modulus increases to a less extent than compressive strength.

By increasing elastic modulus, concrete can generate smaller deformation with the same area of structural members under the same load. Moreover, higher elastic modulus can induce a smaller shrinkage and creep due to the restraining effect of stiffer aggregate (Li, 2011). And therefore the development of high modulus concrete is essential. Concrete is regarded as a two-phase composite material and many theoretical models (e.g. Parallel Model, Series Model and Counto Model) were derived and reported by previous investigators. Chi et al. (2003) found that water/binder ratio and properties of aggregate are two main factors determining the elastic modulus of concrete. Halit (2008) demonstrated that fly ash replacement over 30% decreases the elastic modulus of normal concrete. With a wide range of constituents available for concrete, it is necessary to develop concrete mixture that has high strength as well as high modulus for tall buildings.

The objectives of this study are (i) to optimise concrete mix for high modulus concrete, (ii) to characterise the properties of the high modulus concrete developed and (iii) to apply the high modulus concrete in producing structural members. In the first stage, the composition and proportion of the components of the mixture, including water to cement ratio, types of coarse aggregates, different aggregate contents, and variation of coarse aggregate to fine aggregate ratios were optimised. The key issues in improving the elastic modulus of concrete are to reduce or eliminate the interfacial zone, improve aggregate packing, and improve the modulus of hardened cement paste. In this period, work has been done on the utilisation of different supplementary cementitious materials such as silica fume and metakaolin and minimisation of water/binder ratio by using superplasticizer.

EXPERIMENTAL STUDY

Raw Materials and Mixture Proportions

The raw materials used in this study were ordinary Portland cement (OPC), pulverised fly ash (PFA), condensed silica fume (CSF), 20 mm and 10 mm coarse aggregates (both granite and volcanic), crushed stone fines (S/F), river sand, retarder and superplasticizer (both SP1 and SP2).

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Two different types of coarse aggregate, granite and volcanic, were used in the test. Volcanic has higher strength and elastic modulus than granite, but the same grading. Mixtures were coded such that letters G and V designate granite and volcanic. The target strength levels of Class 1, 2 and 3 concrete were 45 MPa, 60 MPa and 80 MPa, respectively. Meanwhile, some adjustments of mixture proportions were made to investigate the effects on the elastic modulus. Sand ratios were changed to a lower level in Class 1 and 2, and more silica fume was used in Class 3. One additional mixture was made as a replicate of concrete in Class 3 containing river sand rather than stone fines. The mixing proportions are shown in Table 1.

Casting, Curing and Testing of Specimens

Twelve cubes and twelve cylinders were cast for each concrete mixture following ASTM C192. Cubes of 100×100×100 mm were used for cube compression test and cylinders of ϕ 100×200 mm were tested to obtain cylinder compressive strength and elastic modulus. During mixing, cement, crushed stone fines and coarse aggregates were blended first and fly ash, silica fume, superplasticizer and water were then added. All the specimens were molded and compacted by rodding and vibration. After 24 hours, specimens were demolded and stored in curing room at 23°C and 100% relative humidity until testing.

Compressive Strength

The development of compressive strength was measured with testing machine (ADS 2000, Unit Test) at the age of 7, 14, 28 and 56 days. Three 100×100×100 mm cubes for each formula were tested at each age.

Modulus of Elasticity

Material constants of concrete determined by low-strain non-destructive test are called dynamic elastic constants. Dynamic elastic material constants of concrete may be used for quick assessment of material quality and uniformity. Dynamic modulus of concrete was determined by the longitudinal resonant frequency method at 7, 14, 28 and 56 days. The longitudinal resonant frequency method is a kind of non-destructive technique for determining the elastic material constants of a concrete (Jin, 2001). The testing method is based on an accurate three-dimensional vibration analysis of intermediate length cylinders using Rayleigh-Ritz method. The static elastic modulus of concrete was measured with MTS machine at the age of 7, 14, 28 and 56 days according to ASTM C469. Three ϕ 100×200 mm cylinders for each formula were tested at each age.

RESULTS AND DISCUSSION

Influence of Coarse Aggregate

Two different types of coarse aggregate, granite and volcanic, were tested. The compressive strengths of concrete cubes with granite and volcanic aggregates at different ages are shown in Figure 1. There was little difference between the strengths of two different kinds of concrete at the same age. The results indicated that the type of coarse aggregate had insignificant effect on the compressive strength of concrete.

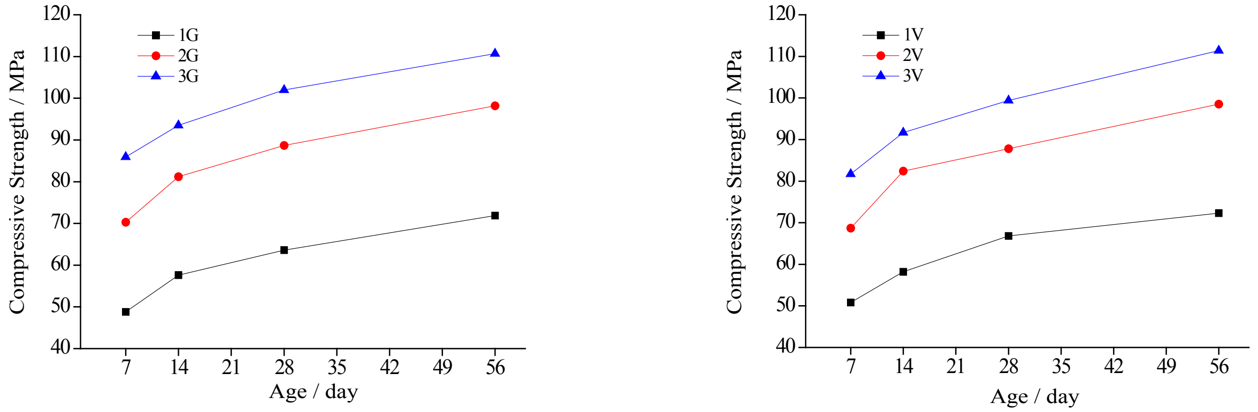
Table 1 Mixture Proportions of Concrete with Different Strength Levels

Class of Concrete	OPC	PFA	CSF	20 mm	10 mm	S/F	Water	Retarder	SP1	SP2	w/c
	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	kg/m³	L/m³	L/m³	L/m³	
1G(C45)	345	115	0	515	415	720	200	2.99	2.0±1.0	0	0.43
2G(C60)	380	125	0	530	430	720	165	0	0	6.0±2.0	0.33
3G(C80)	398	105	32	530	430	740	150	0	0	12.0±2.0	0.28
1V(C45)	345	115	0	515	415	720	200	2.99	2.0±1.0	0	0.43
1V-Less S/F	345	115	0	555	455	640	200	2.99	2.0±1.0	0	0.43
2V(C60)	380	125	0	530	430	720	165	0	0	6.0±2.0	0.33
2V-Less S/F	380	125	0	575	455	640	165	0	0	6.0±2.0	0.33
3V(C80)	398	105	32	530	430	740	150	0	0	12.0±2.0	0.28
3V-More CSF	398	72	65	530	430	740	150	0	0	12.0±2.0	0.28
3V-River sand	398	105	32	530	430	740 (River sand)	150	0	0	12.0±2.0	0.28

Taking concrete with granite aggregate for example, a good linear relationship between cylinder and cubic compressive strength has been obtained (Figure 2). The conversion coefficient was 0.825.

Typical results of dynamic modulus of C60 are listed in Table 2. The results showed that the dynamic elastic modulus testing method had good repeatability and reliability. Thus, the stiffness of concrete can be measured without damaging the specimen.

The elastic moduli of concrete with two different types of coarse aggregates at 28d are listed in Table 3. It can be seen from Table 3 that concrete with volcanic aggregates had higher static elastic modulus since volcanic rock has higher stiffness than granite rock. However, the increments



(a) Granite (b) Volcanic

Figure 1 Compressive Strength of Concrete Cubes with Granite and Volcanic at Different Ages

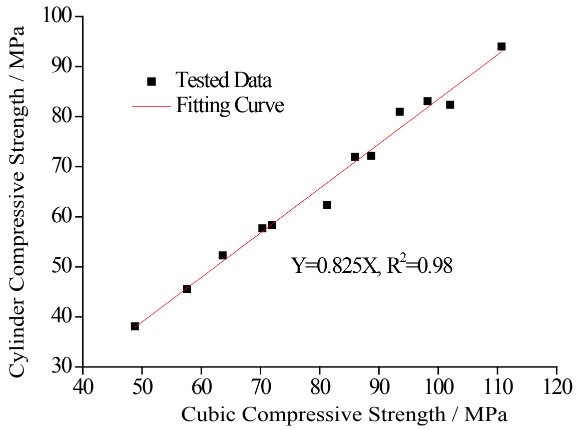


Figure 2 The Relationship between Cylinder and Cubic Compressive Strength

Table 2 Typical Results of Dynamic Modulus of C60 Concrete

Primary Mode (kHz)	Secondary Mode (kHz)	Poisson's Ratio	Dynamic Modulus (GPa)
10.45	19.59	0.286	42.74
10.40	19.64	0.260	42.20
10.27	19.36	0.266	41.13

Table 3 Elastic Modulus of Concrete with Two Different Types of Coarse Aggregate at 28d

Aggregate type	Static Elastic Modulus (GPa)								
	1(C45)			2(C60)			3(C80)		
Granite	33.53	33.80	33.73	38.72	37.26	38.05	39.17	39.82	39.54
Volcanic	36.54	36.12	35.40	40.51	40.45	39.68	40.40	40.84	40.62

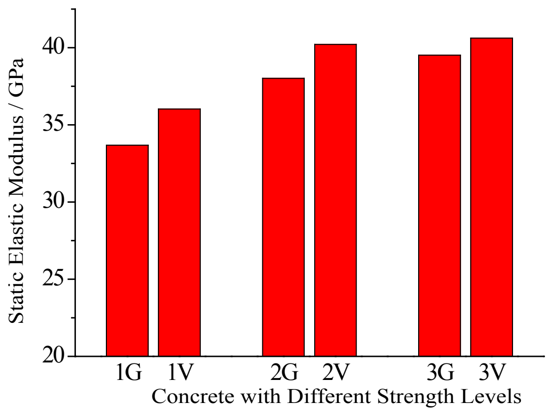


Figure 3 Elastic Modulus of Concrete with Two Different Types of Coarse Aggregate at 28d

of elastic modulus by changing from granite to volcanic for Class 1, 2 and 3 were 6.9%, 5.8% and 2.8%, respectively (Figure 3), revealing that higher stiffness coarse aggregate had smaller influence on the elastic modulus of concrete. On the other hand, concrete with lower water/cement ratio generated larger elastic modulus, proving that minimising w/c ratio was an effective approach to enhance the stiffness.

Influence of Sand Ratio

Previous researchers reported that reducing sand ratio can improve the elastic modulus of concrete. To verify this theory, a 5% reduction of sand ratio from Class 1 and 2 mixture proportions was conducted. However, the final tested results showed that a 5% reduction of sand ratio made the compressive strength go down slightly and it had no obvious influence on the elastic modulus of concrete, which meant that the sand ratios of original mixture proportions were suitable and applicable (Table 4). This was possibly because lower sand ratio made the grading of solid particles inside the concrete not continuous and the porosity increased.

Influence of Silica Fume

During mixing, larger proportion of silica fume made fresh concrete drier and the fluidity reduced. The compressive strength and elastic modulus of two kinds of concrete specimens with different amount of silica fume are listed in Table 5. It can be seen that concrete specimen with more condensed silica fume had a little higher compressive strength than that of less silica fume. More silica fume made little contribution to early elastic modulus but resulted in higher stiffness at 28 days.

Influence of Fine Aggregate (Stone Fines and River Sand)

Since crushed stone fines (artificial sand) used for mixing were too pulverised to provide dense structure of concrete, river sand was replaced as fine aggregate for high modulus concrete. Elastic modulus of such batch of concrete increased dramatically to 46.0 GPa (Table 6). It was obvious that the grading of river sand and its main component, silicon dioxide, were beneficial for making high modulus concrete.

Concrete Specimens after Casting

Static Elastic Modulus Test for Concrete Specimen

Table 4 Compressive Strength and Elastic Modulus of Concrete with Different Sand Ratios

Sand Ratio	Compressive Strength (MPa)		Elastic Modulus (GPa)	
	1V	2V	1V	2V
Normal	57.6	76.5	36.0	40.2
Lower	54.1	71.4	36.2	39.5

Table 5 Compressive Strength and Elastic Modulus of Concrete with Different Proportions of Silica Fume

Specimen No.	Percentage of Silica Fume	Compressive Strength (MPa)		Elastic Modulus (GPa)	
		7 days	28 days	7 days	28 days
3V (C80)	6%	63.9	79.8	37.7	40.7
3V-More CSF	12%	66.2	81.7	37.5	41.4

Table 6 Elastic Modulus of Concrete with Different Kinds of Fine Aggregate

Specimen No.	Fine Aggregate	Elastic Modulus (GPa)	
		7 days	28 days
3V (C80)	Crushed stone fines	37.7	40.7
3V-River sand	River sand	42.1	46.0

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

i. The elastic modulus of concrete depended largely on the mixing proportions and stiffness of aggregates.

ii. Concrete with volcanic aggregates had higher elastic modulus than that with granite aggregates. Concrete with river sand as fine aggregate had higher elastic modulus than that with crushed stone fines. The highest modulus reached in this study was 46 GPa.

iii. A 5% reduction of sand ratio had no influence on the elastic modulus of concrete. Moreover, silica fume at the level of 12% replacement for cement provided higher long-term elastic modulus.

ACKNOWLEDGMENTS

The financial support from the Hong Kong Construction Industry Council under grant of CIC13EG04 is greatly acknowledged.

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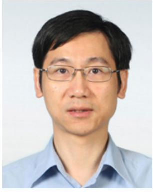
BIOGRAPHY

Dr. Zongjin Li is a Professor at HKUST. His research interest includes durability of concrete; development of high performance concrete; nondestructive testing in civil engineering; development of advanced building products using extrusion technique; functional materials in civil engineering. He has authored or co-authored 3 technical books, edited 3 conference proceedings and published over 300 technical papers. He has also been awarded three US and five Chinese patents and three of them have been developed into commercial products.

Mr. Tianyuan Fan is now a Ph.D. student at the Department of Civil and Environmental Engineering, the Hong Kong University of Science and Technology. His recent research topic is Development of High Modulus Concrete for Tall Buildings sponsored by CIC. He received his M.Sc. in Civil Infrastructural Engineering and Management from HKUST in 2013 and B.Eng. in Civil Engineering from Southeast University (Nanjing, China) in 2012.



Prof. Christopher K.Y. LEUNG is the Head and Professor of the Department of Civil and Environmental Engineering at HKUST. His research interests include composite mechanics, application of fiber composites, fracture mechanics of cementitious materials as well as the mechanics-based design of fiber optic sensors. One of his early research has established the foundation for designing pseudo-ductile cementitious composites with strain-hardening behavior, which has been widely applied in real projects in the US, Japan and China. He has served as Associate Editor of many journals in his field and has received three research-related prizes and awards. Prof. Leung is Fellow of HKIE and RILEM. He is currently serving as the Chairman of the Committee on Productivity and Research under CIC.

Ir Dr. Herbert ZHENG is the General Manager of Concrete Services at Gammon Construction Limited. With over 20 years of experience, Dr. Zheng is specialized in concrete technology and its applications in ready-mixed concrete and construction industries and experienced in managing research & development projects, concrete batching plants and testing laboratories. He also worked as a part-time lecturer in the Department of Civil and Environmental Engineering at HKUST in 2012. Dr. Zheng holds membership of several professional associations and institutes such as ASTM, HKCI, HKIE and ACI.

DEVELOPMENT OF COMPOSITE STRUCTURES FOR ENHANCEMENT OF PRODUCTIVITY AND EFFICIENT UTILISATION OF MANPOWER

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Labor shortage in Hong Kong is an acute problem due to recent bloom in construction industry which leads to the need to raise the skill level of construction workers to increase productivity. In many advanced countries like USA, Japan, China and U.K., steel-concrete composite structures occupy a higher proportion of use in buildings against reinforced concrete, when compared to the case in Hong Kong. As we are approaching the era of knowledge-based society and labour shortage with a likely new design provision for seismic design in the near future, Hong Kong needs to develop an approach for more efficient and cost-effective design of more ductile composite structures where steel members are directly encased inside concrete (or the opposite) to produce a form of steel-concrete composite construction against reinforced concrete where reinforcing bars are used instead of steel stanchion. One may be interested to know that steel-concrete composite structures are common in seismic and non-seismic countries like respectively Japan and U.K. for the reason of lack of and high cost in manpower in doing bar-fixing and Hong Kong seems to be facing a similar problem. This project further enhances the design technology for composite buildings with the advantages over existing buildings as (1) enhanced productivity with manpower or construction works reduced with less steel bar fixing works (2) faster speed of construction as the steel part could take temporary loads during construction and composite action resists permanent load (3) higher ductility against dynamic and cyclic forces like seismic loads (4) smaller member size leading to smaller loads on foundation and (5) lighter member size leading to more usable area and more economical and sustainable design by accurate evaluation of capacity of structural members.

Keywords: advanced analysis, codes of practice, composite structures, economical structural design.

BACKGROUND

Labour shortage in Hong Kong is an acute problem due to recent bloom in construction industry which leads to the need to raise the skill level of construction workers to increase productivity. In many advanced countries like USA, Japan, China and U.K., steel-concrete composite structures occupy a higher proportion of use in buildings against reinforced concrete and steel structures, when compared to the case in Hong Kong. As we are approaching the era of knowledge-based society and labour shortage with a likely new design provision for seismic design in the near future, Hong Kong needs to develop an approach for more efficient and cost-effective design of more ductile composite structures where steel members are directly encased inside concrete (or the opposite) to produce a form of steel-concrete composite construction against reinforced concrete where reinforcing bars are used instead of steel stanchion.

One may be interested to know that steel-concrete composite structures are common in seismic and non-seismic countries like respectively Japan and U.K. for the reason of lack of and high cost in manpower in doing bar-fixing and Hong Kong seems to be facing a similar problem.

The advantages of composite structures over reinforced concrete and bare steel structures include many aspects as:

i. Productivity will be enhanced and manpower or construction works will be reduced with less steel bar fixing works;

ii. Faster speed of construction, provided that the industry has experience in this construction form because the steel part could take temporary loads during construction and composite action resists permanent loads;

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iii. Higher ductility against dynamic and cyclic forces like seismic loads and smaller member size leading to smaller loads on foundation;

vi. Lighter member size leading to more usable area; and

v. More economical and sustainable design by accurate evaluation of capacity of structural members.

STEPS TO ELIMINATE DRAWBACKS OF COMPOSITE STRUCTURES

The disadvantage of composite construction is generally viewed as higher cost because of heavier use of more expensive steel material and greater difficulty in modification of structural forms at a later stage. This research project is aimed at eliminating these disadvantages by adoption of more efficient construction and design methods such as use of higher strength grip bolts in connections to replace the welded connections and use of efficient couplers to link a concrete beam to a steel column in case the former is still preferred. Advanced design can further be utilised to reduce steel weight. Further, the second-order direct analysis method of design, a new design method developed by the proposer of this project over decades of research and appeared in various advanced national design codes will be applied to design of the structural form via consideration of new features associated with composite construction such as use of semi-rigid joints for more accurate design against strength, ductility and stiffness. The project will benefit the industry and to the society in norm and enhance the competitiveness of local engineers in designing more advanced and efficient structures.

EVOLUTION OF STRUCTURAL DESIGN TECHNOLOGY IN COMPUTER AND I-CLOUD AGE

Before the recent introduction of the new design codes in many places like Hong Kong, engineers still use the linear analysis with subsequent manual or spread-sheet type of design to carry out the safety check of steel structures. This process involves many limitations such as unreliability and sometimes inadequately safe design because the buckling lengths of some key elements in a frame are not reliably assessed and yielding is not allowed for in the linear analysis. For example, the effective length or checking of member buckling is assumed at the undeformed stage of a structure and this assumption is incorrect once deflection, yielding or cracking occurs or when the structure deforms such that the buckling length is varied. In the checking by linear analysis, prescriptive formulae in codes were applied to assess instability and yielding in the members. This implies more effort is placed on design part to compensate for a coarse first-order analysis in safety check. No information is generally available for ductility performance of a structure in the aspect of the robustness and resistance against progressive collapse. This old linear analysis design is still dominantly used in practice but, newly published codes such as the Eurocode-3 (2005) and 4 (2006), LFRD (2010), AS4100 (2000) and Hong Kong Steel Code (2011) put the new second-order analysis method of design in favor of the old effective length method. This project further applies the application of this new design method to composite structures. Conventional ultimate and serviceability limit state design, design for progressive collapse, fire and seismic engineering of structures can be carried out directly by the new design approach. This project attempts to make the design applicable to virtually all structural forms.

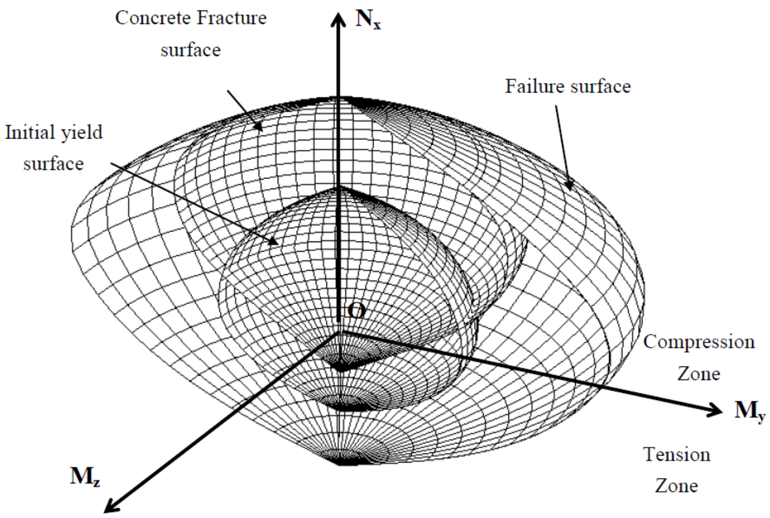

Figure 1 Failure, Initial Crack and Fracture Surfaces for Concrete

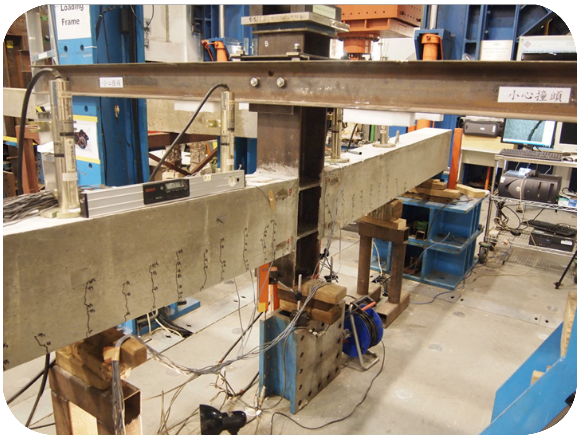

Figure 2 Testing of a Concrete Beam to Steel Column Connection

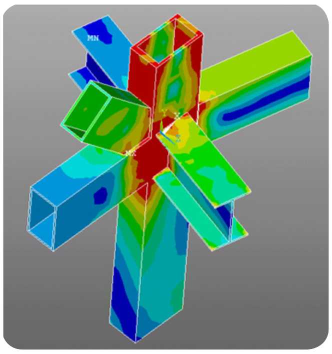

Figure 3 Nonlinear Finite Element Analysis of a Complex Joint for a Concrete Filled Hollow Sections and I-beams

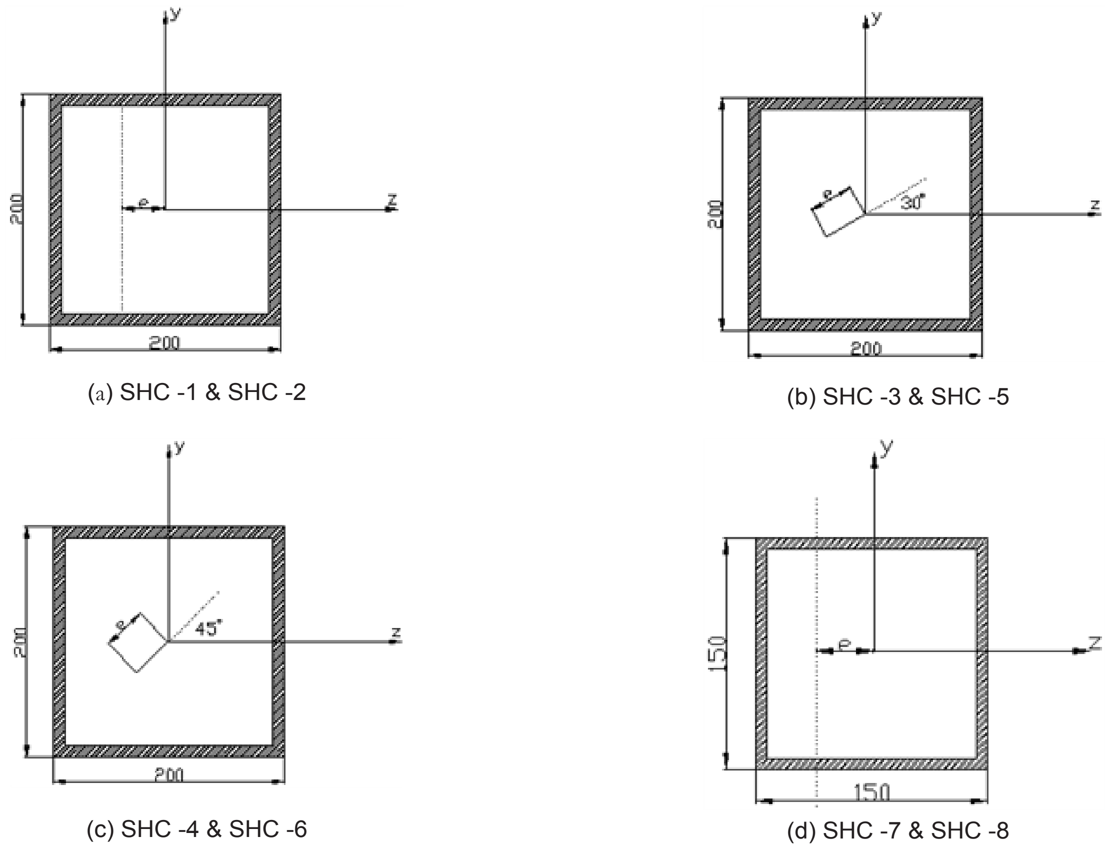

Figure 4 Cross Section Properties and Eccentricity of Loading

The finding of this project provides engineers a competitive alternative in choice of building materials and structural form and there will be more performance-based design that engineers only need to demonstrate the adequacy of his structural system against different requirements and scenarios.

The key issues for materialising the proposed new structural form under conventional load cases and unconventional scenarios like fire, seismic engineering and progressive collapse due to accidental damage of structural members rely on development of a computer method. This project develops a reliable computer-based design approach capturing the buckling behaviour and material yielding. Efficient computer modeling in the analysis software is needed as it not only saves computer time, but it also makes the model simple and consistent with the current model for a linear, old or traditional analysis which suffers from the lack of sufficient information after yielding and significant deflection occurs in a structure. The authors have also successfully developed an element capable of capturing the essential characteristics for elastic-plastic buckling (see Zhou and Chan, 1995) and the element needs to be refined for yielding with unloading. This change of design concept is a non-trivial task as many structural analysis and design programs are still based on old element like the Hermite cubic element ignoring initial and load-induced curvature because the old element is assumed always straight in its formulation.

OUTCOMES OF THIS PROJECT

i. Develop an elasto-plastic design method for composite structures allowing for complex crack and fracture surfaces for concrete like the interactive yield and failure surfaces in Figure 1;

ii. Formulate design technique allowing for pinned, rigid and semi-rigid connections with more uses of high-strength bolts than welds for saving of manpower and better quality assurance. Members of different materials can be connected efficiently and safely like Figure 2 for a reinforced concrete beam to steel column connection which takes advantages of these two materials;

iii. Derive a rational model for plastic-hinge analysis of composite, steel and reinforced concrete structures for economical structural design;

vi. Verify the accuracy of the methods against experimental test and code formulae; and

v. Propose a unified, robust and practical second-order analysis and design method for steel, reinforced concrete and composite structures under various scenarios.

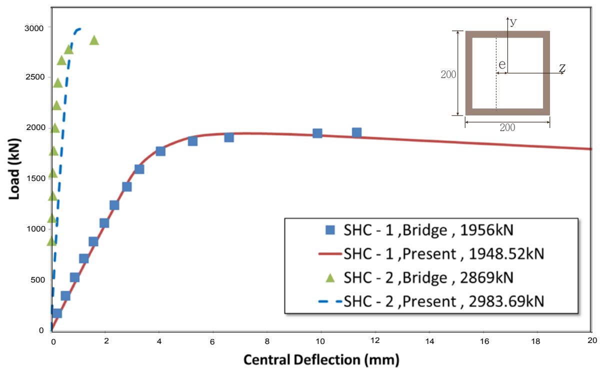

Figure 5 Load – Central Deflection Curve for SHC -1 & SHC -2

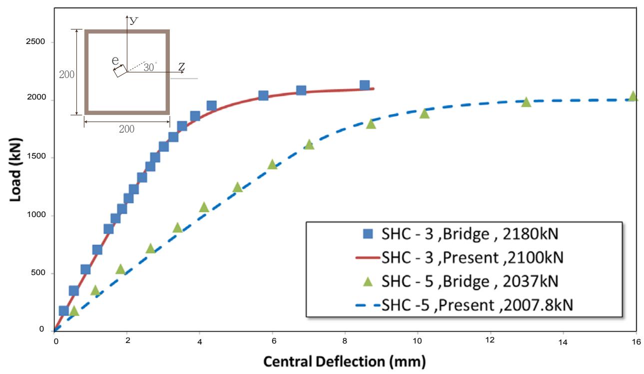

Figure 6 Load – Central Deflection Curve for SHC -3 & SHC -5

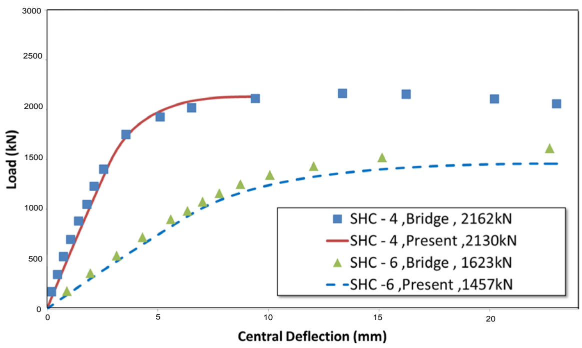

Figure 7 Load – Central Deflection Curve for SHC -4 & SHC -6

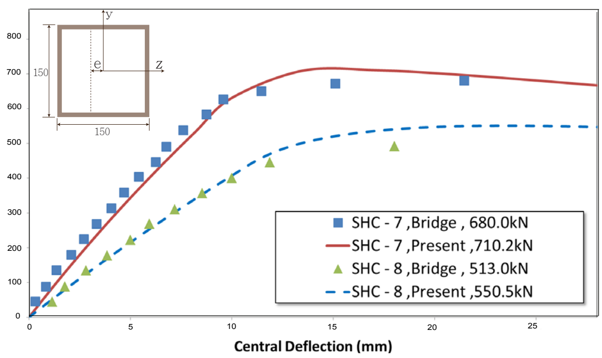

Figure 8 Load – Central Deflection Curve for SHC -7 & SHC -8

VERIFICATIONS AGAINST EXPERIMENTAL TESTS ON CONCRETE FILLED HOLLOW COLUMNS

There have been many examples studied by the proposed method in the project (see Liu et al., 2012) and this session demonstrates one of these verifications. Eight pin-ended concrete filled square steel tubes subjected to various directions of eccentric loads are analysed and compared with the test results by Bridge (1976). This present study focuses on both the predictions of failure load and the experimental load vs. deflection curves. Connections of the composite members can also be modeled and analysed as shown in Figure 3. The cross section properties and load condition are shown in Figure 4. Full details of these test specimens can be found in the paper for the tests by Bridges (1976).

In these examples, all columns are assumed to possess initial imperfections equals to L/1000 in the numerical analysis and the minimum residual displacement method (Chan, 1987) is adopted for tracing of equilibrium path in the inelastic analysis. The applied loads and total displacement at the mid span of eight columns are shown from Figures 5 to 8. These figures show a good co-relation between the theory and the tests and confirm the accuracy of the proposed theory.

From the comparison results shown above, the proposed approach indicates highly accurate prediction for the load vs.deflection path of the individual concrete filled tubular columns until reaching the failure loads. It shows that the numerical results are very well compared with the tests in uniaxial as well as the biaxial bending cases. Both the initial yield and failure loads and deflections by the proposed theory also agree vey well with the test results. It should also be noticed that the cracking effects in these columns are modeled otherwise the predicted ulitimate loads will be higher than the test results.

CONCLUSIONS AND FURTHER DEVELOPMENT

The combined use of composite structures is not new in Hong Kong and has been employed in linking concrete beams to H-piles and steel columns but its widespread use in construction of superstructures is not materialised. In Hong Kong, many buildings are constructed on small sites with limited areas and sometimes irregular site geometry that building reinforced concrete structure is wasteful and expensive in use of land because of huge column size and heavy loads on foundation. To reduce member size and loads on foundation, lighter and more slender steel-concrete composite structures can be a potential replacement option. This paper describes the pros and cons of the structural form and suggests advanced and efficient techniques to design structures of different materials and shapes, completely in line with the popular Eurocode and local codes for buildings. The developed new design method has been used successfully in projects in Hong Kong, Macau, Mainland and Singapore.

Parties interested in the design method described in this paper could contact CIC for further information.

ACKNOWLEDGEMENTS

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BROGRAPHY

Professor S.L. Chan is currently a Chair Professor in Computational Structural Engineering in Department of Civil and Environmental Engineering at the Hong Kong Polytechnic University and the chief consultant of the Code of Practice for Structural Use of Steel 2005 and 2011. He published more than 300 papers in journals, books, conferences and keynote/ invited papers in major steel conferences overseas.

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Dr. S.W. Liu is currently a Research Associate in Department of Civil and Environmental Engineering at the Hong Kong Polytechnic University. His research is mainly focused on the advanced analysis and design of hybrid steel and concrete structures and developed software for biaxial bending analysis of reinforced concrete and composite columns and he is involved heavily with the development of software.

HARMONISED MEMBER BUCKLING DESIGN IN STRUCTURAL EUROCODES

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The Eurocodes are a new set of European structural design codes for building and civil engineering works, and they are intended to be mandatory for European public works. Indeed, they are likely to become the de-facto standards for the private sector in Europe. 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. All the structural Eurocodes had been published as full European Standards (ENs) in 2007, and since then, they have been adopted as well as practiced in a number of countries worldwide in additional to those member states of the European Union.

Owing to the withdrawal of various British structural design standards in March 2010, the Works Department of the Government of Hong Kong SAR have been migrating to Eurocodes in stages for the design of public works civil engineering structures while mandatory adoption of Eurocodes will commence in 2015. Moreover, as many countries, in particular, Asian countries, have already adopted the structural Eurocodes for design and construction of building structures, there is a growing need for design and construction engineers in Hong Kong to acquire the new skills.

In this paper, the harmonised member buckling design of steel beams and columns as well as steel-concrete composite columns at both room and elevated temperatures is presented together with both the theoretical background and the practical design procedures. It is shown that in the Structural Eurocodes, an effective use of a suitable structural parameter, that is, the normalised slenderness ratio, adopts the same design formulation for member buckling design of various types of structural members, provided that different values are selected for various parameters. Hence, this design method may be regarded as a generalised method readily applicable to many structural members as well as systems.

Keywords: composite structures, Eurocodes, steel structures, structural engineering design, structures.

INTRODUCTION

Globalisation is surely affecting us in various walks of life these days. After decades of infrastructure construction and technological advances in transportation, aviation as well as electronic superhighways, the world is ‘flat’. Hokkaido, Xian, Bangkok, Kular Lumpur and Perth are neighbours in a real and practical sense. We all live in a global village.

In the construction industry nowadays, it is very trendy for engineers to think and talk about international professional recognition, worldwide consultancy service, and regional if not global codes of practice. In the last century, people considered hardship to leave home for work as they anticipate complete isolation from their families and folks for months if not years. Nowadays, people travel light and afar. They communicate through e-mails and short-text messages (SMS) all over the world. Friends and e-Friends are just facebook away!

In the construction industry, it is a very common scene these days for a Korean contractor to work in Dubai for an Australian construction project led by an American architect and designed by a group of Singapore and Hong Kong engineers, using many constructional materials and building products shipped from all over the world: Australia, Belgium, and South Africa. The world has truly evolved into a place that globalisation has already in full swing, shaping our outlook and aspiration.

MODERN STRUCTURAL DESIGN CODES

The Structural Eurocodes are a set of European Standards for the design of buildings as well as civil engineering

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works. They serve as important technical documents for harmonisation of the design and construction requirements in many countries in Europe and beyond. Singapore and Malaysia have already implemented the use of the Structural Eurocodes whilst Hong Kong will soon adopt the Structural Eurocodes in 2015.

Traditionally, a design code is expected to provide all key design requirements and considerations for a structural engineer to perform structural design. Moreover, proven design methods are also provided to assist the structural engineer to justify structural adequacy of a structure in a prescriptive manner, i.e. if a structure is designed and confirmed to satisfy all the design rules, structural adequacy of the structure is deemed to be achieved. However, there is an overriding implicit assumption behind, i.e. the structure being designed is assumed to behave essentially similar to those structures for which the design methods have been developed and derived. While the extreme situation of structural failure would have been prevented, there is little information on how the structure is going to behave towards some specific requirements, in particular, during the serviceability limit states.

A review on the composition of many modern structural design codes reveals a typical layout as follows:

Materials

- Physical, chemical and mechanical properties
- Requirements on structural performance

Sections and Dimensions

- Typical shapes and sizes, limiting dimensions and scope of applications

Section Capacities

- Section capacities under single actions
- Section capacities under combined actions

Member Resistances

- Member resistances under single actions
- Member resistances under combined actions

System Behaviour

Connection Design

- Force analysis methods
- Basic resistances of fasteners, fixings and connectors
- Detailing rules

All these topics are considered to be essential for effective control on the design of a structure, and the given layout is considered to be a simple, effective, and structured arrangement to assist a structural engineer to perform his design in a straight forward manner.

In practice, the design code is often considered to be a legal document for a structural engineer in many incidents to perform his statutory duty to his client as well as to the regulatory authority. Consequently, the design clauses in the code are often written and compiled in a prescriptive approach, i.e. everything is spelled out with every use cautioned and every limit defined. While the majority of the design clauses are well controlled, there are occasions that the design becomes grossly conservative or things become unnecessarily complicated when interpretation between the lines of the design clauses is required, or the design is operating beyond the intended use of the design clauses. Hence, the prescriptive approach is generally considered to be restrictive, and little information is provided once the limits of the design clauses are crossed. Moreover, it is generally difficult to know how efficient the design is.

Modern Design Approach

With recent advances in design development of structural design codes, performance-based approach should be considered as a major advancement which enables rational design and analysis on the structural behaviour of a structure against well defined requirements at specific levels of acceptance. This approach is commonly adopted in seismic design as well as fire resistant design of building structures and bridges whilst the levels of structural responses and acceptability are explicitly defined for specific structures. It is obvious that in order to achieve effective performance-based design, it requires a high level of understanding to the structural behaviour and responses of the structures. Hence, structural examination on selected critical members is, in general, insufficient, and it is necessary to have numerical simulation on the entire structure, i.e. to examine the structural behaviour of the entire structures under specific performance requirements. Supplementary member checks may be carried out, whenever necessary.

Ideally, a design method in a modern design code should be formulated in such a way that a structural engineer is able to perform the design with comprehension on its principles when working through the design procedures. Moreover, the design procedures should be complied in a fashion that the structural engineer is able to make choices on the calculation efforts he is prepared to give against the structural accuracy and economy of the structure he requires. He should be able to decide whether it is sufficient to adopt simple and yet conservative data, or it is necessary to evaluate specific design parameters precisely according to the situation he is dealing with. When the structural engineer is making choices and decisions as the design proceeds, he is able to control the design more rationally, i.e. to engineer not just the final product, but also the design process.

HARMONISED DESIGN RULES

It is very interesting to review the development of a number of national steel codes, and to examine some of the design methods and clauses which have evolved over the years; an illustration on member buckling check is given below. It is about to see how the use of the slenderness of a member which is a structural parameter derived from structural mechanics against elastic buckling facilitates simple and direct evaluation of member resistances for hot rolled steel columns and beams, cold formed steel columns and beams, as well as composite columns.

Member Buckling Check for Hot Rolled Steel Sections

Consider the member buckling check in the British Steel Code BS5950 (BSI, 2000) and the Hong Kong Steel Code (BD, Hong Kong SAR, 2012). For a column susceptible to axial buckling, the slenderness of the column, λ, has been established for many years, and it is defined as follows:

$$\lambda = \frac{L_E}{r_y} \qquad (1)$$

where

L_E is the effective length of the column, depending on its boundary conditions; and

r_y is the radius of gyration of the cross-section of the column, depending on cross-section geometry.

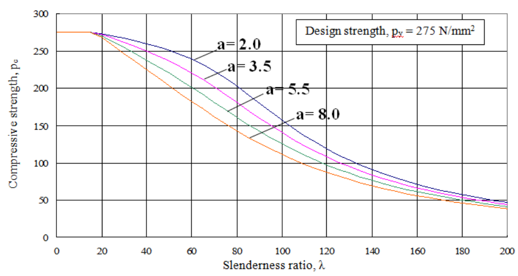
It should be noted that λ is an important structural parameter of a column which is a direct measure of the tendency of the column undergoing elastic buckling. Through a non-linear interaction curve, which is commonly referred as the Perry-Robertson formula, the effect of axial buckling in a real column is expressed as *a reduction in its design strength from its yield value*, i.e. *a compressive strength*. The compressive strength of a real column with material and geometrical initial imperfection is readily obtained through a specific column buckling curve after considering material yielding and geometrical instability. It should be noted that based on the section shapes and sizes as well as the bending axes during buckling of the columns, a total of four column buckling curves are established, as shown in Figure 1a, after careful calibration against test data. For columns with fabricated sections made of thick steel plates, the design methodology is the same although the design yield strengths of the columns should be reduced by 20 N/mm^2 to allow for the presence of high residual stresses due to welding.

For a beam susceptible to lateral buckling, an equivalent slenderness of the beam, λ_{LT} , is devised, and it is defined as follows:

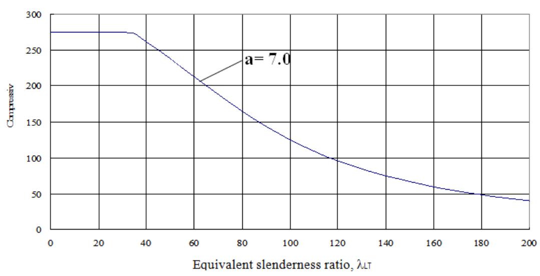
$$\lambda_{LT} = uv\lambda \qquad (2)$$

where u and v are secondary section properties of the beam related to lateral bending and torsion.

The adoption of the equivalent slenderness of the beam is a good example of harmonised codification, and both the design parameters, u and v, may be considered to be correction factors which enable lateral buckling check of a beam to be performed in a way very similar to axial buckling

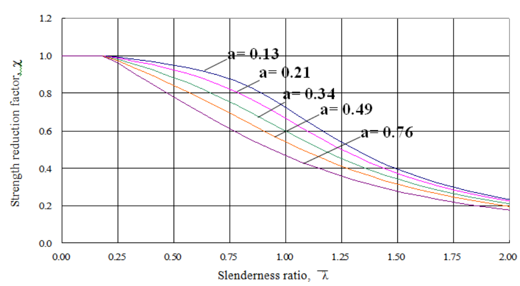


a) Column buckling curves

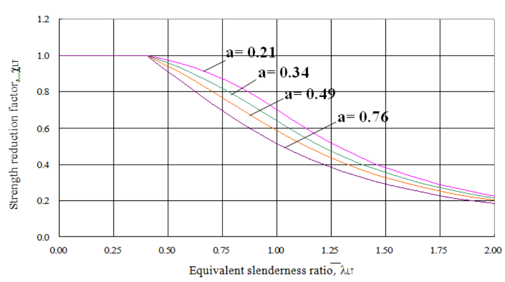


b) Beam buckling curve

Figure 1 Member Buckling Curves to BS5950 Part 1



a) Column buckling curves



b) Beam buckling curves

Figure 2 Member Buckling Curves to EC3 Part 1.1

check of a column. Hence, the effect of lateral buckling in a real beam is expressed as *a reduction in its design strength from its yield value*, i.e. *a bending strength*. The bending strength of a real beam with material and geometrical initial imperfection is readily obtained after considering material yielding and geometrical instability, as shown in Figure 1b. It should be noted that there is only one beam buckling curve in BS5950 while different design coefficients are adopted for hot rolled and fabricated beam sections. For standardised steel sections, tabulated values of u and v are readily found in section dimensions and properties tables.

Hence, it is demonstrated that in both buckling checks of columns and beams, the design methods are considered to be highly structured and rationally, and all design parameters and coefficients are derived explicitly with analytical formulation. However, it should be noted that the structural adequacy and economy of the design methods often hinge on one single value, the effective length of the member. Up to the very present, there is still little or no effective means to examine the buckling behaviour of a particular member in a structure except through advanced finite element modelling, and the determination of the effective length of the member, and hence, the member slenderness, remains largely empirical.

Member Buckling Check using Normalised Slenderness

It is interesting to note that the harmonised design checks for both axial and lateral buckling of steel members given in BS5950 have been adopted in Eurocode 3 (BSI, 2003) with different formulation. The design rules are re-formulated in such a way that the effect of member buckling in real steel columns and beams are expressed as *a reduction to the resistance of the cross-sections*, i.e. a strength reduction factor, χ_c multiplied to the axial compression resistance of the cross-section of the member, and a strength reduction factor, χ_b multiplied to the moment resistances of the cross-section of the member respectively. Moreover, modified slenderness ratios are adopted, and they are defined as follows:

$$\bar{\lambda} = \frac{\lambda}{\lambda_1} \quad \text{or} \quad \sqrt{\frac{N_{c,Rd}}{N_{cr}}} \qquad (3)$$

for axial buckling of columns

and

$$\bar{\lambda}_{LT} = \frac{\lambda}{\lambda_1} \quad \text{or} \quad \sqrt{\frac{M_{c,Rd}}{M_{cr}}} \qquad (4)$$

for lateral buckling of beams

where

λ_1 is a material parameter given by:

$$= \pi \sqrt{\frac{E}{f_y}} \; ;$$

E is the elastic modulus of steel;

f_y is the design yield strength of steel;

$N_{c,Rd}$ is the design axial resistance of the column;

N_{cr} is the elastic critical buckling resistance of the column;

$$= \pi^2 \frac{E\,I}{L_{cr}^{\;2}} \; ;$$

I is the second moment of area of the cross-section of the column;

L_{cr} is the buckling length;

$M_{c,Rd}$ is the design moment resistance of the beam; and

M_{cr} is the elastic critical buckling moment resistance of the beam

It should be noted that the modified slenderness ratio is defined either as a ratio of the geometrical slenderness to the material parameter of the member, or a ratio of the square root of the cross-sectional resistance of the member to its corresponding elastic critical buckling resistance. Hence, the design methods are "normalised" against the mechanical properties of the members, and they are equally applicable to other materials, such as other metal and timber mebers, provided that calibration against geometrical and mechanical initial imperfections has been performed. As shown in Figure 2, there are five different buckling curves for columns while four for beams, and the selection depends on section types and sizes as well as bending axes, if applicable. Refer to Appendices A1 and B1 for detailed formulation.

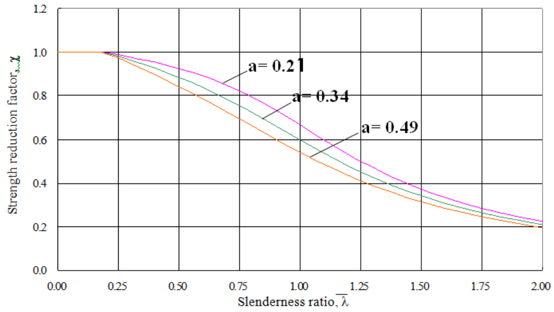


Figure 3 Member Buckling Curves to EC4 Part 1.1

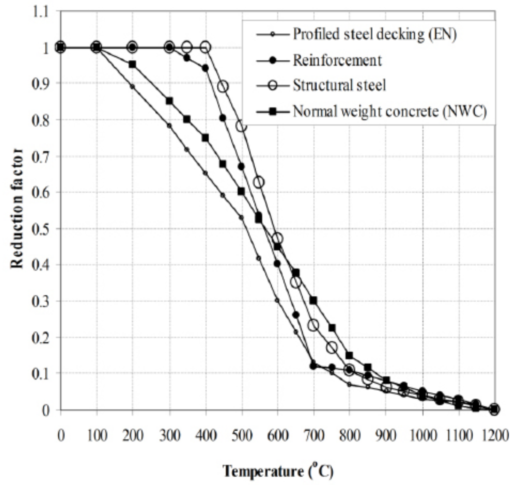


Figure 4 Strength Reduction Factors

Member Buckling Check for Composite Columns

For composite columns with concrete encased H sections or concrete in-filled hollow sections, the same design methodology has been adopted in Eurocode 4 (BSI, 2004), and the axial buckling resistances of the composite columns are based on the modified slenderness ratio which is defined as follows:

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rd}}{N_{cr}}} \quad (5)$$

where

$N_{pl,Rd}$ is the design plastic resistance of the composite section, and it is equal to the sum of the section capacities of individual components: concrete core, steel W and steel reinforcement;

N_{cr} is the elastic axial buckling resistance of the composite column;

$= \pi^2 \frac{(EI)_{eff}}{L_{cr}^2}$

$(EI)_{eff}$ is the effective flexural rigidity of the composite column, and it is equal to the sum of the effective flexural rigidities of individual components: concrete core,steel section and steel reinforcement;

L_{cr} is the buckling length.

Hence, the effect of axial buckling in real composite columns is expressed as a strength reduction to the resistances of the cross-sections of the members, i.e. a strength reduction factor, χ_c , multiplied to the compression resistances of the cross-sections of the composite columns. Refer to Appendix C1 for detailed formulation. As shown in Figure 3, there are three different column buckling curves, and the selection depends on the section types and the bending axes.

Consequently, it is demonstrated that by adopting the same design methodology, i.e. a slenderness ratio of a member or its associated resistance ratio, the effect of buckling is readily expressed as a strength reduction factor multiplied to the resistance of the cross-section of the member. The same methodology is shown to be highly satisfactorily in both steel and composite columns as well as steel and composite beams. Moreover, adoption of different buckling curves enables wide coverage of cross-sections of different shapes and sizes as well as bending axes when the members buckle.

Member Buckling Check for Steel and Composite Columns at Elevated Temperatures

It should be noted that based on rigorous material tests of a number of constructional materials at elevated temperatures, various sets of strength reduction factors are given in EN 1993-1-2: 2005 and EN1994-1-2: 2005 may be found for general use. Figure 4 plots these factors for different constructional materials for easy reference. It is interesting to note that all of these materials retain only 50% of their original strengths when their temperatures reach 500 to 600 °C.

Based on a known temperature distribution within a structural member obtained either from fire tests or numerical heat transfer analyses, the resistance of the member at elevated temperature may be readily evaluated according to Parts 1.2 of EN 1993-1-2 and EN1994-1-2. Refer to Appendices A2, B2 and C2 for detailed formulation. Flow charts on various design procedures on steel beams and columns as well as steel-concrete composite columns at both normal and elevated temperatures are provided in Appendices A3, B3 and C3 to facilitate the use of these design procedures in practical design.

CONCLUSIONS

Owing to the successful design development on member buckling in the Structural Eurocodes, the normalised slenderness ratios of steel beams and columns as well as steel-concrete composite columns are shown to be effective to determine corresponding strength reduction factors due to member buckling. Moreover, the same design formulation for member buckling design of various types of structural members is readily used together with parameters having different values according to the materials of the members. Hence, the harmonised member buckling design of steel beams and columns as well as steel-concrete composite columns at both room and elevated temperatures is presented in this paper, and this design method may be regarded as a generalized method readily applicable to various structural members.

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BIOGRAPHY

Prof. K F Chung is a renowned academic, researcher and structural engineer with established expertise in steel construction. Currently, Professor Chung is Associate Head (Academic Development) of the Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, President of the Hong Kong Constructional Metal Structures Association, and Council Member of the Institution of Structural Engineers.

Prof. Chung works on a wide range of inter-disciplinary engineering analysis and design, especially on modern steel and composite building structures. His research interests include limit state analysis and performance-based design of structural systems, structural fire engineering and fire protection in buildings and tunnels, and design codification.

Appendix A

Design procedure of a pinned-pinned column to EN 1993: 1-1 & 2: 2005

A1 Cold design of a steel column against axial buckling

1. Evaluate the slenderness, λ of the steel column

2. Evaluate the equivalent slenderness, $\bar{\lambda}$ of the steel column

$$\bar{\lambda} = \frac{\lambda}{\lambda_1} \qquad \text{where} \qquad \lambda_1 = \pi\sqrt{\frac{E}{f_y}}$$

or

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}}$$ for Class 1 and 2 sections

where A is the section area
f_y is the yield strength

$$N_{cr} = \frac{\pi^2 EI}{L_{cr}^2}$$ which is the critical buckling load

L_{cr} is the buckling length

3. Evaluate ϕ

$$\phi = 0.5\,[1+\alpha(\bar{\lambda}-0.2)+\bar{\lambda}^2]$$

where α is the imperfection factor

4. Evaluate the reduction factor, χ

$$\chi = \frac{1}{\phi+\sqrt{\phi^2-\bar{\lambda}^2}} \qquad \text{but } \chi \le 1.0$$

5. Evaluate the buckling resistance, $N_{b,Rd}$

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}}$$

where γ_{M1} is the material factor for the steel column

A2 Hot design of a steel column against axial buckling

1. Evaluate the slenderness, λ of the steel column

2. Evaluate the equivalent slenderness, $\bar{\lambda}$ of the steel column

$$\bar{\lambda} = \frac{\lambda}{\lambda_1} \qquad \text{where} \qquad \lambda_1 = \pi\sqrt{\frac{E}{f_y}}$$

or

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}}$$ for Class 1 and 2 sections

where A is the cross-sectional area
f_y is the yield strength
$N_{cr} = \pi^2 \frac{EI}{L_{cr}^2}$ which is the critical buckling load
L_{cr} is the buckling length

3. Evaluate the non-dimensional slenderness $\bar{\lambda}_\theta$

$$\bar{\lambda}_\theta = \bar{\lambda}\sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}}$$

4. Find out the reduction factors for both yield strength and Young's modulus i.e. $k_{y,\theta}$ and $k_{E,\theta}$

5. Evaluate ϕ_θ

$$\phi_\theta = 0.5[1+\alpha\bar{\lambda}_\theta+\bar{\lambda}_\theta^2]$$

where α is the imperfection factor, $\alpha = 0.65\sqrt{\frac{235}{f_y}}$

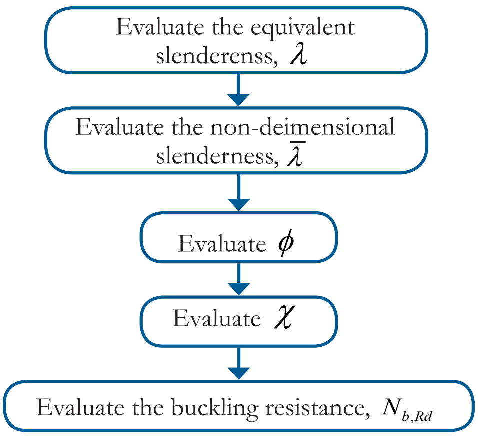
6. Evaluate the reduction factor, χ_{fi}

$$\chi_{fi} = \frac{1}{\phi_\theta+\sqrt{\phi_\theta^2-\bar{\lambda}_\theta^2}}$$

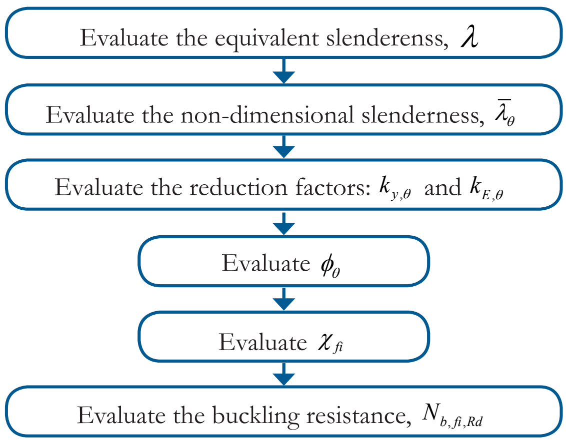
7. Evaluate the buckling resistance, $N_{b,fi,Rd}$

$$N_{b,fi,Rd} = \frac{\chi_{fi} A k_{y,\theta} f_y}{\gamma_{M1}}$$

A3 Flow charts for cold design



Flow charts for hot design



Appendix B

Design procedure of an unrestrained beam to EN 1993: 1-1 & 2: 2005

B1 Cold design of a steel beam against lateral torsional buckling

1. Evaluate the slenderness, λ_{LT} of the steel beam

$$\lambda_{LT} = uv\lambda\sqrt{\beta_w}$$

where u is the buckling parameter
v is the slenderness factor
λ is the slenderness of the steel beam
β_w is equal to 1.0 for Class 1 and Class 2 sections

2. Evaluate the non-dimensional slenderness $\bar{\lambda}_{LT}$

$$\bar{\lambda}_{LT} = \frac{\lambda_{LT}}{\lambda_1}$$

where $\lambda_1 = \pi\sqrt{\frac{E}{f_y}}$

3. Evaluate ϕ_{LT}

$$\phi_{LT} = 0.5\,[1 + \alpha_{LT}(\bar{\lambda}_{LT} - \bar{\lambda}_{LT,0}) + \beta\bar{\lambda}_{LT}^{\,2}]$$

where α_{LT} is the imperfection factor
$\bar{\lambda}_{LT,0}$=0.4
$\beta = 0.75$

4. Evaluate the reduction factor, χ_{LT}

$$\chi_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^{\,2} - \beta\bar{\lambda}_{LT}^{\,2}}} \quad \text{but} \quad \chi_{LT} \le 1.0$$

5. Evaluate the modified reduction factor, $\chi_{LT,\text{mod}}$

$$\chi_{LT,\text{mod}} = \frac{\chi_{LT}}{f}$$

where f is the correction factor for the moment distribution

6. Evaluate the buckling moment resistance, $M_{b,Rd}$

$$M_{b,Rd} = \chi_{LT,\text{mod}} W_y \frac{f_y}{\gamma_{M1}}$$

B2 Hot design of a steel beam against lateral torsional buckling

1. Evaluate the equivalent slenderness, λ_{LT} of the steel beam

$$\lambda_{LT} = uv\lambda\sqrt{\beta_w}$$

where u is the buckling parameter
v is the slenderness factor
λ is the slenderness of the steel beam
β_w is equal to 1.0 for Class 1 and Class 2 sections

2. Evaluate the non-dimensional slenderness $\bar{\lambda}_{LT,\theta,com}$

$$\bar{\lambda}_{LT,\theta,com} = \frac{\lambda_{LT}}{\lambda_1}\sqrt{\frac{k_{y,\theta,com}}{k_{E,\theta,com}}}$$

where $\lambda_1 = \pi\sqrt{\frac{E}{f_y}}$

3. Find out the reduction factors for both yield strength and Young's modulus i.e. $k_{y,\theta,com}$ and $k_{E,\theta,com}$

4. Evaluate $\phi_{LT,\theta,com}$

$$\phi_{LT,\theta,com} = 0.5[1 + \alpha_{LT}\bar{\lambda}_{LT,\theta,com} + \bar{\lambda}_{LT,\theta,com}^{\,2}]$$

where α_{LT} is the imperfection factor

$$\alpha_{LT} = 0.65\sqrt{235/f_y}$$

5 Evaluate the reduction factor, $\chi_{LT,fi}$

$$\chi_{LT,fi} = \frac{1}{\phi_{LT,\theta,com} + \sqrt{\phi_{LT,\theta,com}^{\,2} - \bar{\lambda}_{LT,\theta,com}^{\,2}}}$$

6. Evaluate the modified reduction factor, $\chi_{LT,fi,\text{mod}}$

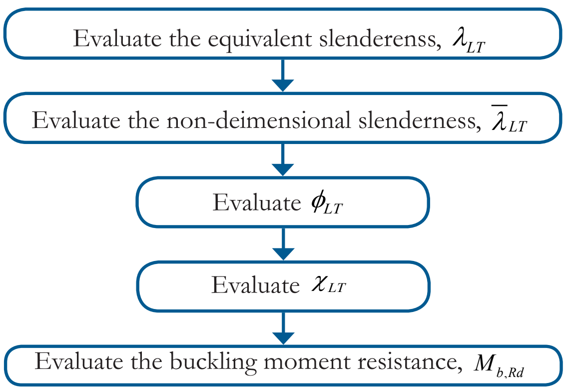
$$\chi_{LT,fi,\text{mod}} = \frac{\chi_{LT,fi}}{f}$$

where f is the correction factor for the moment distribution

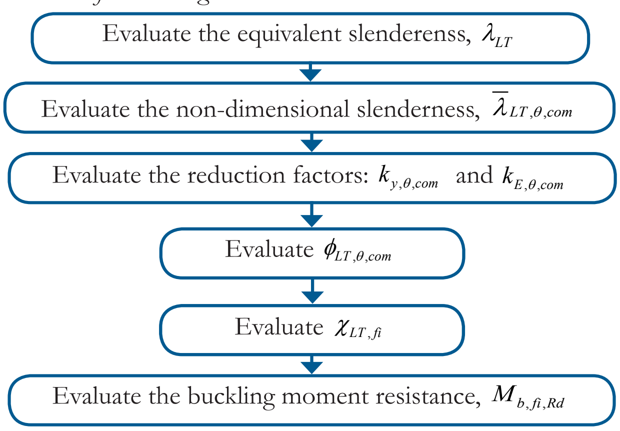
7. Evaluate the buckling moment resistance, $M_{b,fi,Rd}$

$$M_{b,fi,Rd} = \chi_{LT,fi} k_{y,\theta,com} W_y \frac{f_y}{\gamma_{M1}}$$

B3 Flow charts for cold design



Flow charts for hot design



Appendix C

Design procedure of a pinned-pinned composite to EN 1994: 1-1 & 2: 2005

C1 *Cold design of a composite column against axial buckling*

1. Evaluate the effective flexural stiffness $(EI)_{eff}$ of the composite column

$$(EI)_{eff} = E_a I_a + E_s I_s + K_e E_{cm} I_c$$

where K_e is a correction factor that should be taken as 0.6
I_s, I_{cm} and I_a are the second moment of area of the structural steel section, the uncracked concrete section and the reinforcement for the bending plane being considered

2. Evaluate the equivalent slenderness, $\bar{\lambda}$ of the steel column

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}}$$

where $N_{pl,Rk}$ is the characteristic value of the plastic resistance to compression

$$N_{cr} = \frac{\pi^2 (EI)_{eff}}{L_{cr}^{\ 2}}$$

which is the critical buckling load
L_{cr} is the buckling length

3. Evaluate ϕ

$$\phi = 0.5\ [1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2]$$

where α is the imperfection factor

4. Evaluate the reduction factor, χ

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \qquad \text{but } \chi \le 1.0$$

5. Evaluate the buckling resistance, $N_{b,Rd}$

$$N_{b,Rd} = \chi N_{pl,Rd}$$

where $N_{pl,Rd}$ is the plastic resistance to compression

C2 *Hot design of a composite column against axial buckling*

1. Evaluate the effective flexural stiffness $(EI)_{eff}$ of the composite column

$$(EI)_{fi,eff} = \phi_{a,\theta} E_{a,\theta} I_{a,\theta} + \phi_{s,\theta} E_{s,\theta} I_{s,\theta} + f_{c,\theta} E_{cm} I_{c,\theta}$$

where $\phi_{i,\theta}$ is the reduction coefficient depending on the effect of thermal stresses
$I_{i,\theta}$ is the second moment of area of the partially reduced part I of the cross section for bending about the major or the minor axis

2. Evaluate the equivalent slenderness, $\bar{\lambda}_\theta$ of the steel column

$$\bar{\lambda}_\theta = \sqrt{\frac{N_{fi,pl,R}}{N_{fi,cr}}}$$

where $N_{pl,R}$ is the plastic resistance to compression with material factors taken as 1.0

$$N_{fi,cr} = \frac{\pi^2 (EI)_{fi,eff}}{L_\theta^{\ 2}}$$

which is the critical buckling load
L_θ is the buckling length

3. Evaluate ϕ_θ

$$\phi_\theta = 0.5[1 + \alpha(\bar{\lambda}_\theta - 0.2) + \bar{\lambda}_\theta^{\ 2}]$$

where α is the imperfection factor

4. Evaluate the reduction factor, χ_{fi}

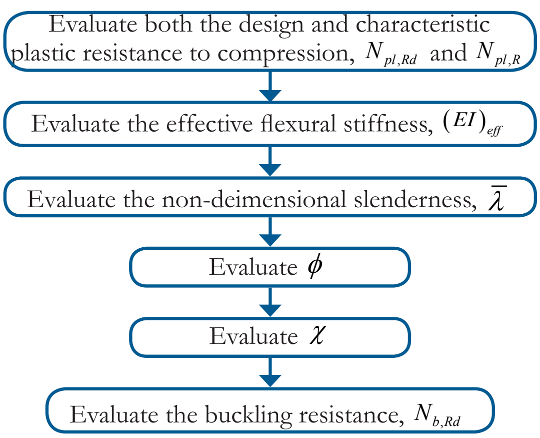
$$\chi_{fi} = \frac{1}{\phi_\theta + \sqrt{\phi_\theta^{\ 2} + \bar{\lambda}_\theta^{\ 2}}}$$

5. Evaluate the buckling resistance, $N_{b,fi,Rd}$

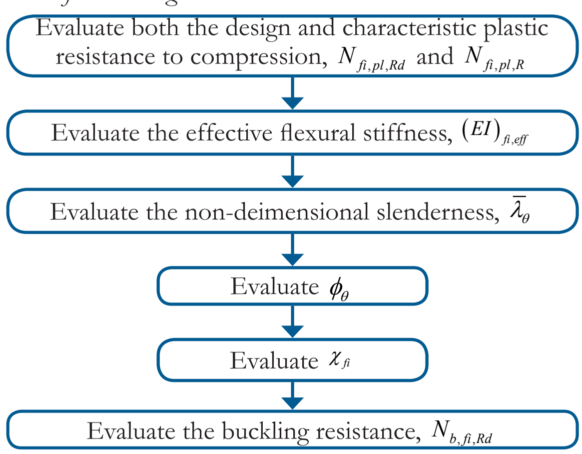
$$N_{fi,Rd} = \chi_{fi} N_{fi,pl,Rd}$$

where $N_{fi,pl,Rd}$ is the plastic resistance to compression

C3 *Flow charts for cold design*



Flow charts for hot design



PRELIMINARY STUDY OF INTERNAL-COMBUSTION-ENGINE PRIMED TRIGENERATION SYSTEMS FOR HIGH-RISE OFFICE BUILDING APPLICATION IN HONG KONG

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Trigeneration, which is used to generate cooling, heat and electrical power, can satisfy the building energy supply and demand with the merits of energy efficiency and carbon emission cut. To quantify its benefits in high-rise office building in Hong Kong, a preliminary study was carried out to evaluate the year-round dynamic performances of various types of internal-combustion-engine primed trigeneration (ICEPT) systems. It was found that the ICEPT systems could reduce the total energy demand from the building by at most 10.9%, as compared to the conventional system powered by the grid electricity. It was also found that the decrease in carbon dioxide emission depended on the prime mover and the fuel involved. For a natural-gas-fuelled ICEPT system, 13.2% of carbon reduction could be achieved. As such, availability of natural gas or biofuels is essential to attain both energy and environmental merits of ICEPT for high-rise building application in Hong Kong.

Keywords: carbon emission cut, energy efficiency, high-rise building, internal combustion engine, trigeneration.

INTRODUCTION

With the urge for reduction in carbon dioxide emission, the design for more energy-efficient power systems has been a hot issue nowadays. One feasible direction is the utilisation of the waste heat from the power systems for heating and/or spacing cooling through the use of heat-driven air-conditioning equipment, thus forming a trigeneration system. The resulting system efficiency can be improved substantially. Al-Sulaiman et al. (2011) reviewed the characteristics of various kinds of trigeneration systems with different prime movers. They remarked that internal-combustion-engine primed trigeneration (ICEPT) systems were commonly designed. Wu and Wang (2006) highlighted the benefits of applying ICEPT systems to small- or medium-capacity applications. The merit of ICEPT systems depends on how frequent co-generation/trigeneration is required. In Hong Kong, most of the office buildings are multi-storey and that air-conditioning is usually required throughout the entire year with only limited heating demand in the perimeter zone during the winter time. Hence, it is highly probable that the adoption of ICEPT systems can lead to satisfactory results. To analyse, the year-round dynamic performance of three types of ICEPT systems, namely diesel engine fuelled by diesel oil, gas engine fuelled by natural gas and gas engine fuelled by petrol gas, are investigated when applied to a high-rise office building in Hong Kong. The corresponding system energy demands and the carbon dioxide emission levels are compared with those based on the conventional system powered by the grid electricity.

SYSTEM DESCRIPTION

Figure 1 shows the schematic diagram of the ICEPT system employed in this study. The waste heat from the engine jacket and the exhaust gas are recovered through the jacket and exhaust heat exchangers. The recovered heat is used to drive single-effect absorption chiller and to provide space heating when necessary. A three-way control valve is used to regulate the flow rate of regenerative water entering the absorption chiller based on the chilled water return temperature. To keep the space heating water temperature at the common design level (i.e. between 45 and 55°C), a space heating heat exchanger is employed. An auxiliary water cooler is included which operates when the utilisation of the recovered heat is low in order to maintain the jacket water temperature entering the engine at the desired level. To minimise the loading of the auxiliary water cooler, the regenerative water will bypass the exhaust heat exchanger when the auxiliary water cooler is switched on.

A reference office building with 30 storeys high as detailed in EMSD (2007) was employed for the study. Each floor was divided into three zones, namely the exterior zone, the interior zone and the lift lobby. The design total

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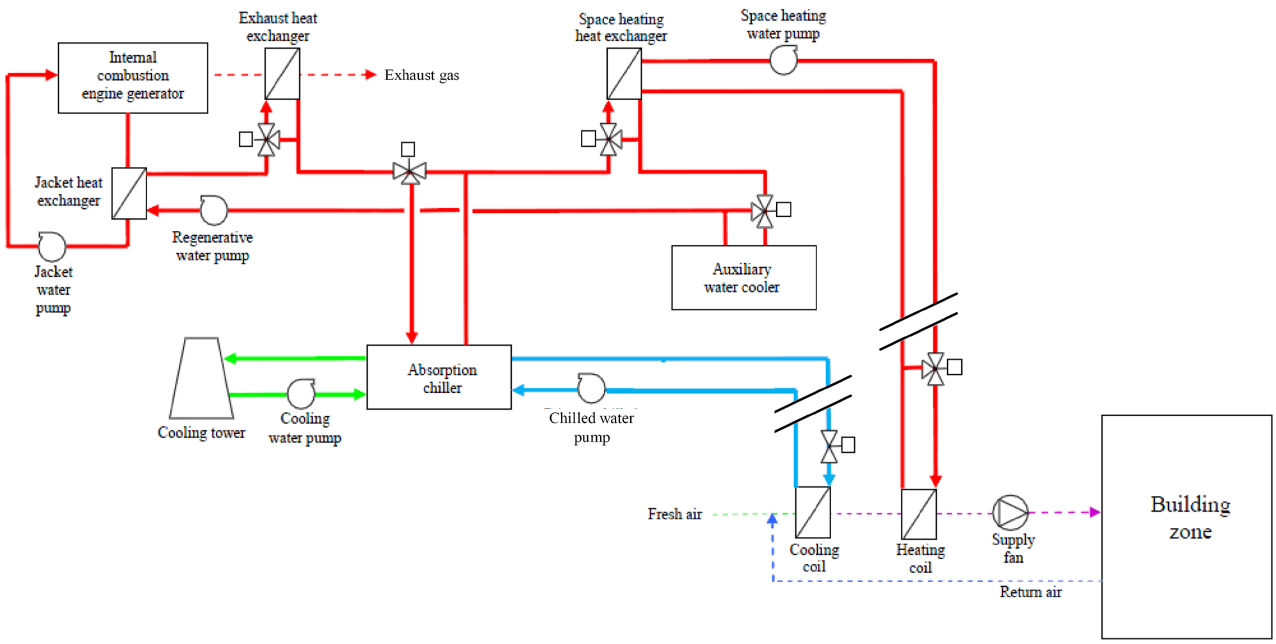

Figure 1 Schematic Diagram of an Internal-Combustion-Engine-Primed Trigeneration System

Table 1 Comparison of Year-Round Performance of the Various Trigeneration Systems with that for the Conventional System

System	Total electricity demand from building (MWh)	Total electricity supply from ICEPT system (MWh)	Total electricity supply from grid (MWh)	Total energy input to ICEPT system (MWh)	Carbon dioxide emission (Ton)
Conventional	7,979	Not applicable	7,979	Not applicable	5,585
ICEPT system fuelled by diesel oil	7,187 (↓ 9.9%)	5,948	1,307	18,936	5,681 (↑ 1.7%)
ICEPT system fuelled by natural gas	7,106 (↓ 10.9%)	5,761	1,374	19,675	4,848 (↓ 13.2%)
ICEPT system fuelled by petrol gas	7,124 (↓ 10.7%)	5,848	1,332	19,400	5,495 (↓ 1.6%)

cooling load was 4,568 kW based on the design indoor and outdoor conditions of 24°C/54%RH and 32.8°C/71% respectively. Space heating was provided at the exterior zone by using hot water heating coils. The design total heating capacity was 766 kW under the design indoor and outdoor temperatures of 21 and 10°C respectively. The corresponding peak electrical demand was 2,554 kW based on the conventional design and the loading schedules as stated in EMSD (2007). In view of the high ratio of the cooling to electric load requirements, auxiliary vapour-compression chiller was necessary to meet the air-conditioning demand. Two sets of engine generators and single-effect absorption chillers were employed with one set of water-cooled vapour-compression chiller adopted. The performance of the proposed trigeneration system was compared with a conventional HVAC system comprising three sets of water-cooled vapour-compression chillers. Electric duct heaters were used in the exterior zone to provide space heating in the conventional system.

MODEL DEVELOPMENT

To perform the year-round dynamic system simulations, the engineering simulation program TRNSYS (2011) was employed. TRNSYS offered an interactive interface to build the system. Each piece of equipment is represented by a component which could be linked to each other as designed. Most of the components required in the ICEPT systems were based on the simulation program TRNSYS (2011), including the building zone (Type56), the pump/fan (Type3), the auxiliary water-cooled vapour-compression chiller (Type666), the cooling tower (Type51), the cooling

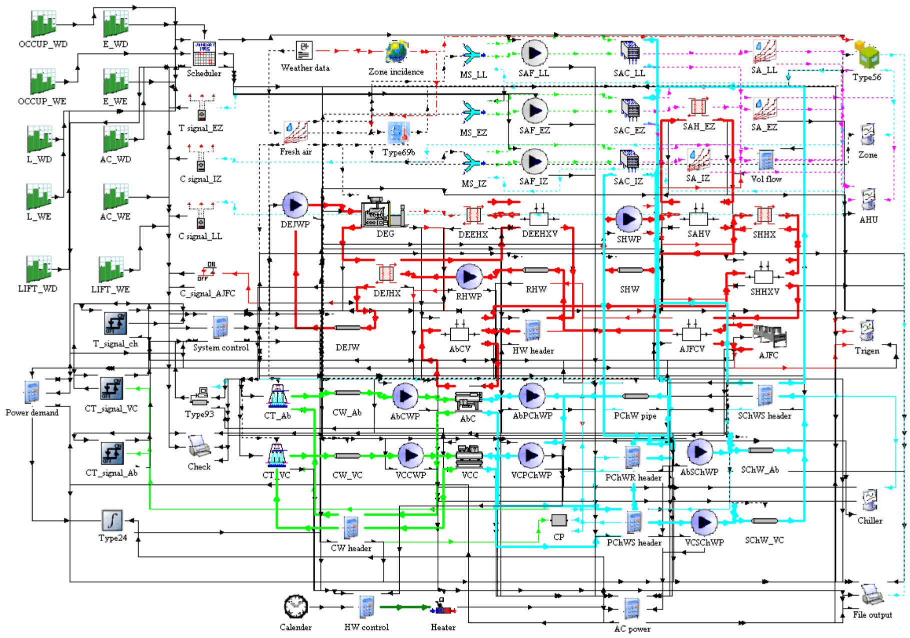

Figure 2 Component Association of the Internal-Combustion-Engine-Primed Trigeneration System in TRNSYS

coil (Type52), the auxiliary water cooler (Type511) and the heat exchanger (Type5). Figure 2 depicts the component association of the ICEPT system developed in TRNSYS.

In this study, new components were developed for the absorption chiller and the internal combustion engine generator. Fong et al. (2012) previously outlined a mathematical model for a single-effect LiBr absorption chiller which was employed in this study. For the internal combustion engine generator, simple four-stroke Otto and Diesel cycles were adopted for the gas and diesel engines. To determine the heat transfer to the jacket water and the energy lost to the ambient air, an averaged cylinder temperature was calculated together with the employment of unified heat transfer values for the jacket and the casing. Year-round dynamic simulations were performed on the TRNSYS platform under the typical meteorological data for Hong Kong (Chan et al., 2006). To avoid the engines to be operated at a very low part-load ratio, auxiliary electricity backup from the grid was required to serve the building during the time when the electrical demand was low. The first generator was energised if the total electricity demand reached 50% of the rated capacity of each generator. The second generator was switched on when the total electricity demand exceeded 150% of the rated capacity of each generator, and remained in operation until the total electricity demand dropped below 140% of the rated capacity of each generator. Decane was selected as the fuel for the diesel engine. The natural gas was assumed to be 100% methane, and that the petrol gas was composed of 60% propane and 40% butane by volume.

RESULTS AND DISCUSSIONS

Table 1 compares the year-round performance of the three ICEPT systems investigated with that based on the conventional system. The rated electrical efficiencies of the diesel engine, natural-gas-fuelled gas engine and petrol-gas-fuelled gas engine were 31.2%, 29.1% and 29.9% respectively which were similar to those indicated in ASHRAE (2004) for naturally-aspirated systems. It could be found that with the adoption of the ICEPT systems, the total electricity demand from the building decreased by at most 10.9% for the ICEPT system fuelled by natural gas. This could be explained by the fact the electrical efficiency was the lowest for this type of ICEPT system which implied that more waste heat was available for the absorption chillers and a smaller auxiliary vapour-compression chiller could be used. However, this could not outweigh the adverse effect due to the lower electrical efficiency and the total energy input to the natural-gas-fuelled ICEPT system was still the highest. The sum of the total electricity supply from the ICEPT system and the grid was slightly higher than that consumed by the building. The reason was that the efficiencies of the ICEPT systems were assumed to remain constant during the part-load operation. Hence, a linear correlation was adopted between the fuel injection rate and the required ICEPT system output. This might not be fully appropriate so that the ICEPT system might over-supply electricity to the building at some instants which contributed to an electricity surplus.

From Table 1, the total carbon dioxide emission was the lowest for the natural-gas-fuelled ICEPT system which corresponded to 13.2% reduction as compared to that for the conventional system. On the other hand, no saving was achieved by using the diesel-oil-fuelled one. The benefit was minimal when the petrol-gas-fuelled ICEPT system was adopted. The main reason was that the carbon dioxide emission index for the local grid electricity supply was only 0.7 kg/kWh (EPD, 2008). This was comparatively lower than that based on a conventional coal-fired power station due to the fuel mix adopted by the local power company and the utilisation of nuclear power. To improve the situations, ICEPT systems with higher electrical efficiencies through the adoption of more advanced cycles should be considered.

CONCLUSIONS

The energy and environmental merits of the ICEPT systems applied in high-rise office building in Hong Kong were analysed in this preliminary study. Three types of ICEPT systems, namely those fuelled by diesel oil, natural gas and petrol gas, were considered. The system models of ICEPT were established on the simulation platform TRNSYS, and the major components included internal combustion engine, absorption chiller, vapour-compression chiller, cooling tower, auxiliary water cooler, heat exchangers, water pumps, air handling unit, as well as the building zone. Year-round dynamic simulations were performed and the results compared with that based on a conventional system powered by the grid electricity. It was found that the employment of the ICEPT systems all led to a reduction in the total energy demand from the building. The maximum saving was 10.9% with natural-gas-fuelled ICEPT system. However, the energy input from the fuel was also the highest due to its lower electrical efficiency. Meanwhile, the reduction in the carbon dioxide emission was related to the type of prime mover, which could reach at 13.2% for the natural-gas-fuelled ICEPT system. Supply of natural gas or biofuels is highly recommended, in order to reduce the carbon dioxide emission through the employment of ICEPT systems in Hong Kong. In the further study, the effect of electrical efficiency of prime movers will be reviewed, and performance evaluation of trigeneration using other types of prime movers will be conducted.

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S-HELMET: A PROACTIVE CONSTRUCTION SAFETY MANAGEMENT SYSTEM BASED ON REAL-TIME LOCALISATION

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Construction site accidents account for nearly one-fifth of all the industrial accidents in Hong Kong. It would be highly desirable to have a proactive safety management system able to continuously monitor workers' locations and automatically issue warning alarm. This research describes s-Helmet, a system for construction safety based on the real-time localisation technique. In s-Helmet, wireless tags are attached to the safety helmets of workers and moving objects to track their locations in real time. When a worker is moving near danger zones (e.g. edge of the working platform, close to moving objects or electric discharge, etc.), the helmet will automatically issue an alarm to the worker as well as the construction site coordinators. The preliminary results of s-Helmet show its great potential to avoid the construction accidents and its great impact on the construction safety in Hong Kong.

Keywords: construction site management, construction site safety, real-time localisation system.

INTRODUCTION

The high-risk construction industry in Hong Kong accounted for nearly one-fifth of all the industrial accidents. As compared to other places in Asia, such as Japan, South Korea, Taiwan and Singapore, Hong Kong accidents rates on sites stood the highest among all.

Table 1 lists the causes of construction accidents in Hong Kong in 2010 (Labour Department, 2010). It can be seen that the first fatal and non-fatal causes of accidents are 'fall of person from height' and 'striking against by moving object', respectively. It can be seen that, a proactive safety management system would be conceivably preferable which is able to continuously monitor the locations of workers and automatically issue warning alarm.

Obviously, the key in this system is real-time localisation of construction workers. For example, if we know a worker is moving to some danger zones (e.g. edge of the working platform, close to moving objects or electric discharge, etc.), we can issue an alarm to the worker. However, realising such a system is not an easy task. The accuracy of localisation technologies, their sensitivity and adaptability to working conditions and the rate at which information is provided strongly affect the quality of the system. Specifically, we define the following requirements for localisation:

Accuracy

The localisation accuracy should be within 1~2 meters in the presence of possible interferences in the construction sites.

Table 1 Causes of Construction Accidents in Hong Kong (2010)

Causes of Construction Accidents in Hong Kong (2010)				
Top-5 type of accident (Fatal)			Top-5 type of accident (Non-fatal)	
	No of Cases	%		No. of Cases
Fall of person from height	6	23	Striking against by moving object	786
Striking against by moving object	2	8	Slip or fall on same level	581
Contact with moving machinery or object being machined	2	8	Injured whilst carrying	551
Contact with electrical discharge	1	4	Fall of person from height	407

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Updating Frequency

Considering the speed of the workers and the moving objects in the construction site, the real-time location information should be transmitted to the server side no more than 1 second.

Deployment

The system should be easily to be deployed on the construction sites. Tags can be easily attached to the workers and the moving objects without violating existing safety policies.

The Number of Objects to be Tracked

In a 100x100 m^2 area, the number of objects/workers to be tracked simultaneously should be no less than 100.

EXISTING LOCALISATION TECHNOLOGIES

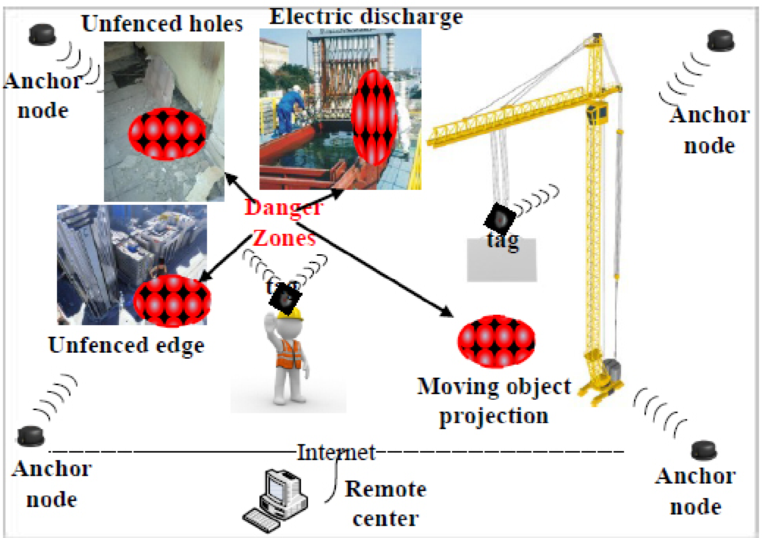
It can be seen that compared with other tracking techniques, the ultra wide band (UWB) technology has some special advantages (Nanotron, 2010). For example, it has high localisation accuracy and low latency and is able to be used in both indoor and outdoor environments without necessitating priory site survey. In addition, UWB technology is robust to the multi-path interference and hence can be used to complicated environment such as construction site.

SYSTEM OVERVIEW

Figure 1(a) gives a basic description of the s-Helmet. The construction site coordinator can define different types of danger zones, which can be unfenced holes and building edges, electric discharge and the ground level projection of

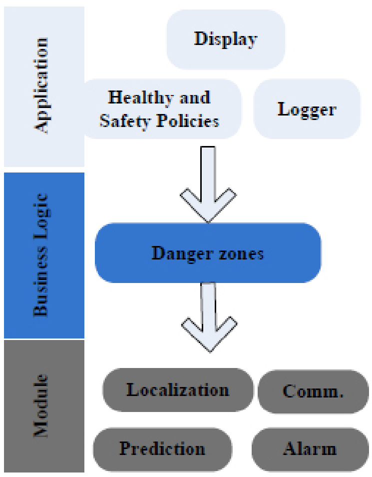
Table 2 Comparison of Existing Localisation Technologies

Tracking Technology	Location Accuracy	Latency	Range	Applicable Environment	Required Site Survey
GPS-based	5-10 m	>10s	N/A	Outdoor	No
Differential GPS	10 cm	>10s	N/A	Outdoor	No
Passive RFID	1 m	<1s	1-10 m	Indoor	No
RSSI	3-10 m	<1s	100-500 m	indoor/outdoor	Yes
Ultrasounds	10 cm	<1s	5 m	Indoor/outdoor	No
Cellular Network	50-500 m	high	N/A	indoor/outdoor	Yes
UWB-based	10cm-1m	low	100~200m	indoor/outdoor	No



(a)

Figure 1(a) The Overview of the System to be Developed



(b)

Figure 1(b) Software Architecture of the System

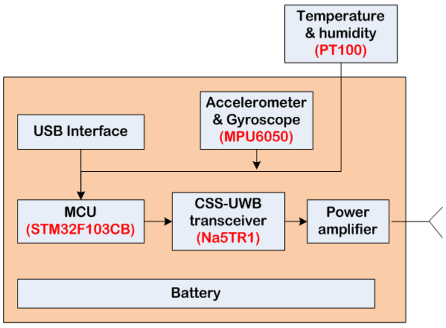


Figure 2(a) The Hardware Design of the s-Helemt

Figure 2(b) The s-Helemt

moving suspended loads, as shown in the figure. To monitor the locations of construction workers and the mechanical devices, four anchors are deployed at different corners of the construction site. Each object to be tracked is attached with a tag. By communicating with the anchors, each tag is able to determine its 3D location. This location information is then sent, also through wireless communication to a remote center which is connected to the internet. When the workers are approaching to these pre-defined danger zones, alarm will be issued to the worker through vibration or beep, and this alarm will also be sent to the coordinator for record.

Figure 1(b) illustrates application software of this system. This software has three tiered architectures. The lowest level implements sensor, localisation, communication, prediction and alarm issuing. The middle level 'business logics' implements high level task oriented functionalities (e.g. when and how managing danger zone or collision avoidance tools included in the lowest level, transferring those data to the high level application modules). The application layer (highest level) customises general business logic functionalities to specific application domain, such as healthy and safety policies.

HARDWARE DESIGN OF S-HELMET

The hardware design of the s-Helmet is shown in Figure 2(a).

The s-Helmet utilises CSS-UWB transceiver as the localisation unit. In addition, an inertial measurement unit (MPU6050) which includes a 3-axis accelerometers and a gyroscope is also included. The MPU6050 can provide the yaw information when it is moving. This information utilised to help the CSS-UWB transceiver for localisation. The s-Helmet adopts STM32 as the central controller. The whole localisation unit is attached to the inner liner of a typical safety helmet (shown in Figure 2(b)).

LOCALISATION SOFTWARE OF THE S-HELMET

In order to improve accuracy of our system, we have conducted several key technologies during the software implementation.

The key technology from s-Helmet is Kalman filter (Welch at el., 1995). Kalman filter is an algorithm that uses a series of measurements observed over time, containing noise (random variations) and other inaccuracies, and produces estimates of unknown variables that tend to be more precise than those based on a single measurement alone. More formally, the Kalman filter operates recursively on streams of noisy input data to produce a statistically optimal estimate of the underlying system state. In our software system, we take the input of distance information between tags and anchors, and estimate the most probable locations for the tags. For the sake of accuracy, we also take information from gyroscope sensor into account. The angle information of the safety helmet can help to make the algorithm more robust rather than use distance information alone. The following is how the algorithm works.

$$X(k+1) = AX(k) + W(k) \quad (1)$$

where $X(k)$ is the state variable, $W(k)$ represents the process noise with covariance matrix Q. $X(k)$ is defined as:

$$X(k) = [D_x(k)\ D_y(k)\ V_x(k)\ V_y(k)]^T \quad (2)$$

$D_x(k)$, $D_y(k)$ represent the location of node in two dimensions, and $V_x(k)$, $V_y(k)$ are the corresponding speed. A is the state transformation matrix and is defined as:

$$A = \begin{bmatrix} 1 & 0 & \Delta T & 0 \\ 0 & 1 & 0 & \Delta T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where ΔT is the updating period.

The measurement equation is defined as

$$Z(k) = f(X(k)) + V(k) \qquad (4)$$

where Z(k) is the measurement vector and V is the measurement noise with covariance matrix R. $Z(k) = [(Z_x(k)\ Z_y(k)\ V_0(k)]^T$ is the measurements and $Z_x(k)$ and $Z_y(k)$ are the x and y locations obtained from the CSS-UWB transceiver, and $V_0(k)$ is the yaw information provided by the MPU6050. In particular, f(X(k)) is defined as:

$$f(X(k)) = \begin{bmatrix} D_x(k) \\ D_y(k) \\ \operatorname{actan}\frac{V_y(k)}{V_x(k)} \end{bmatrix} \qquad (5)$$

The measurement equation is non-linear with respect to the state variables. The corresponding linearised measurement equation H is defined as

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{V_y}{V_y^2(k)+V_x^2(k)} & \frac{V_x}{V_y^2(k)+V_x^2(k)} \end{bmatrix} \qquad (6)$$

Using Kalman filter in an iterative manner:

$$X(k \mid k - 1) = AX(k - 1) \qquad (7)$$

$$P(k \mid k - 1) = AP(k - 1) \times A^T + Q \qquad (8)$$

$$K(k) = P(k \mid k - 1) \times H^T(k)(H(k) \times P(k \mid k - 1) \times H^T(k) + R)^T \qquad (9)$$

$$X(k) = X(k \mid k - 1) \times K(k)(Z(k) - f(X(k)))^T \qquad (10)$$

$$P(k) = (I - K(k) \times H(k)) \times P(k \mid k - 1) \qquad (11)$$

We can obtain the real-time location of the unit, represented as $D_x(k)$ and $D_y(k)$.

EXPERIMENT

In this section, we perform system performance evaluation by setting up an experiment environment and validate the result in a realistic scenario.

Experiment Setup

We conduct our experiment in the campus of the Hong Kong Polytechnic University. We place four anchors in four corners of our experiment area as shown in the Figure 3. The size of experiment area is 9x6 m^2. We attach one tag inside a safety helmet. And let a person wearing the safety helmet to follow the predesigned traces in a constant speed. Meanwhile, we implement the Kalman filter which generates the estimated locations of the person. The updating frequency of Kalman filter is 2 Hz.

Test Results

The test results are shown in Figure 4. The red dots are the ground-truth route the person is walking and the connected blue dots are corresponding localisation results obtained from Kalman filter.

It can be easily seen that the average error is 0.62 m with standard deviation 0.17 m. This preliminary results show that our system has a very high accuracy.

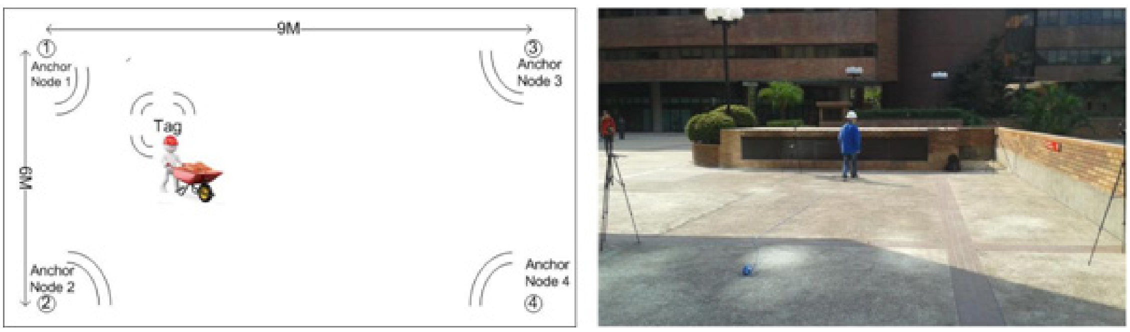


Figure 3 Experiment Environment

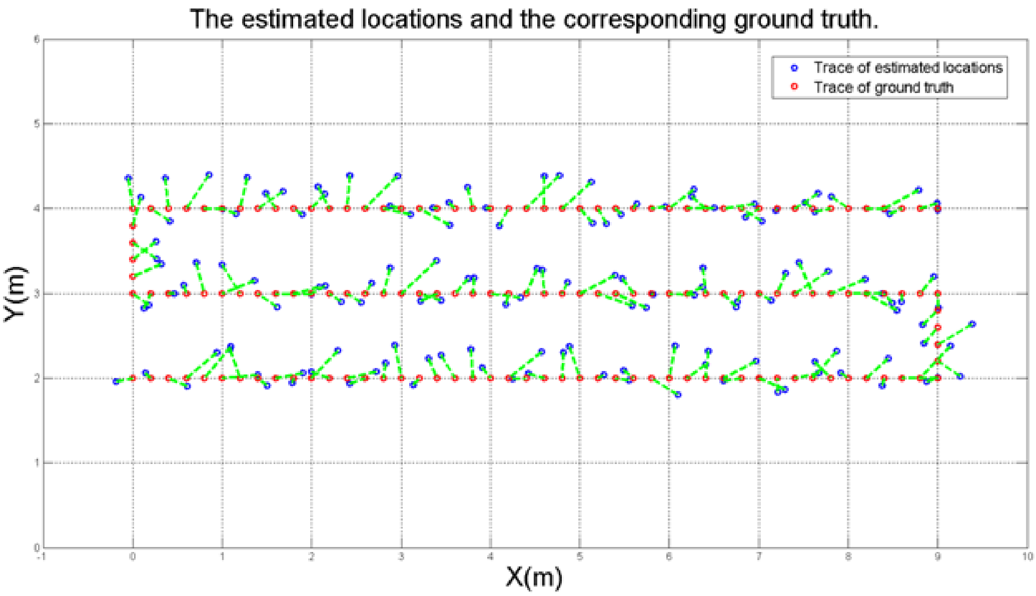


Figure 4 Localisation Result

CONCLUSIONS

In this paper, we propose a novel system called s-Helmet which is able to continuously monitor workers' location and issue warnings automatically based on real-time localisation technology. With wireless tags attached to the safety helmet, the system is able to track the moving workers' location in real-time. When workers are moving towards a danger zone, the system will issue alarms to the workers and notify the site construction side coordinators. The preliminary results show that the system can achieve high accuracy, high updating frequency with a well design Kalman Filter technology.

As part of future work, we plan to evaluate the performance in conducting cooperative localisation algorithm. Implementing the proposed methods in real devices and examining tracking performance and power consumption will also be an important future work.

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BIOGRAPHY

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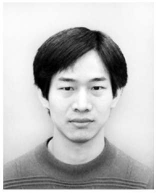

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VIDEO-BASED PROGRESS MEASUREMENT FOR ASSESSING JOBSITE CONCRETE CONSTRUCTION PRODUCTIVITY

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Productivity assessment is an important task both before and during construction, while progress measurement is the key component in productivity assessment. In addition, timely and accurate measurement of work progress on construction sites provides valuable information for project time and cost control. The use of computer vision may provide an opportunity for assisting this particular project management task. Using concrete construction as an example, this paper presents a study in which construction progress was measured by using image processing method. The research results indicate that the proposed method can effectively detect and extract the completed concrete region in the image frames. This potentially facilitates automatic work progress measurement on construction jobsite for productivity assessment purpose.

Keywords: concrete work, processing measurement, productivity assessment, region extraction, video-based computer vision.

INTRODUCTION

Productivity improvement is an important goal for onsite construction project management. Firstly, many developed economies, including Hong Kong, are facing workforce shortage problem in the construction industry. Particularly, many construction companies are suffering from shortage of young workers. As the young workforce in Hong Kong is receiving higher education attainment and more job opportunities, they may find the outdoor working environment such as construction to be less attractive as a career choice. Secondly, the improvement of productivity and the resultant improvement of efficiency will increase project profitability. Therefore, many endeavors have been made in the world for this purpose, especially in western countries. Researchers have attempted to study the process of construction projects for productivity improvement. Traditionally, they hire some specialists to do onsite observation and analysis. However, to obtain comprehensive information, many specialists will be needed for a large construction site, which will cause additional cost. To solve this problem, video surveillance has been introduced to construction projects.

On-site surveillance system can help constructors with productivity assessment through monitoring of the behaviors and activities of on-site workers and/or other on-site working elements. Additionally, this system can assist in safety management and provide the real-time visual information during project coordination meetings that involve different project participants.

Recently, the technology in image processing and computer vision have been greatly advanced, which partially enable the computers to duplicate the abilities of human vision by electronically perceiving and understanding an image (Sonka et al., 1999). Construction video surveillance system could work in conjunction with an intelligent software program to measure and assess onsite productivity. This software program is named as productivity assessment system as further discussed below.

Progress measurement is an important component in the productivity assessment system. The accurate measurement of work in progress on construction sites is vital for productivity assessment, which further assists cost and time control. Traditionally, quantity survey by visual inspection has been used for progress measurement. The monthly measurements, however, are often defected by human errors and low frequency of reliable and effective productivity assessment. The use of computer vision provides an opportunity for assisting this task.

In order to automate the work in progress measurement and the calculation of interim payments and provide an early warning system for potential delays, researchers have been trying to develop an integrated construction progress information system that aims to automatively measure the progress of all kinds of construction activities from digital images captured on site (Zhang, 2009). This system could also avoid some human errors, which are unpredictable and hard to detect on most occasions.

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A few literatures are found to be relevant to this topic. Boukamp (2007) proposed an approach for automating the process of construction specifications by comparing the progress models with the as-built information to support inspection and quality control tasks in construction projects. Leung (2008) a practical construction site presented monitoring system which consists of a long-range wireless network, network cameras, and a web-based collaborative platform. This system can also support project team members to make strategic decisions at vital points during the construction process. Zhang (2009) developed a computer vision system to assist the construction project management.

This paper focuses on the measurement of ongoing concrete works on construction sites, as widely known that concrete is the most important material in civil construction. This study demonstrates the feasibility and efficiency of video-based productivity assessment system.

METHODOLOGY

To measure the progress of concrete work, the region of cement concrete needs to be extracted in the first place. As we can see from Figure 1 that the concrete region in the captured image displays a certain color which is close to gray with slightly green tint. In addition, the concrete region has a homogeneous texture.

Relative image processing techniques and applications were proposed in existing studies. Brilakis (2006) developed a method for retrieving material region by matching known material samples with material clusters within the image content. This method is dependent on the particular color or texture value ranges of a material in an image. However, the chief difficulty is to find appropriate color or texture value ranges. This problem is not sufficiently addressed in their method. Instead of explicitly determining the suitable color or texture value ranges for a certain material, machine learning techniques, which also have been proved successful for region classification in many fields, were also studied for material region detection (Zhu et al., 2010).

Figure 1 The Cement Concrete Region in an Image

As shown in Figure 1, the environment of civil construction is very complicated. The concrete region does not remain uniform, but is disturbed by non-uniform illumination and shadows of on-site objects. This means that some image processing methods must be employed to find the proper cement concrete region in the image. Normally, there are two methods that could be applied. Firstly, we could use spatial filtering method in advance. Because the shadows of on-site objects, as well as the objects themselves, are much smaller compared to the concrete body. This indicates that they can be excluded as image noise by spatial filtering. Secondly, the morphology method can reshape the extracted material region to make it more appropriate.

Moreover, the concrete work in civil construction is typically irrevocable, which means that one location will remain in concrete region once it was finished. This suggests that we can also reshape the concrete region extracted in the time scale. The context information in the image series is very useful for progress measurement. If the concrete region is detected from the current image frame, this means that the image region should appear for the first time in image series and never disappear for all the remaining time. The concrete region could be better adjusted based on these facts.

Figure 2 shows the flow chart of progress measurement for concrete work based on image processing method discussed above. The test images were gathered using a video camcorder. The frame rate is 25p. Frame rate, known as frame frequency, is the rate at which an imaging device produces consecutive images. Commonly, frame rate equals to the number of image frames taken by the camcorder per second. The frame rate of a modern camcorder can be selected; there are three main frame rate standards in the TV and digital cinema business: 24p, 25p, and 30p. For the 25p camcorder, the time difference between two contiguous frames is 0.04 second. However, the progress of the concrete work during 0.04 second is very small. So we can choose the testing frames at a larger time interval or simply use a time-lapse camcorder. Spatial filtering methods are used in image preprocessing period to reduce the influence of shadows and non-uniform illumination. This is followed by reshaping the concrete region both in a single frame and time scale. After that, the progress measurement of concrete work is summarised.

EXPERIMENT ANALYSIS

The frame rate of the testing video is decreased to 12p, and we chose five frames evenly from the video for progress measurement experiment. The five images are shown in Figure 3. The frame interval between adjacent testing images is 3000, so the passing time between two adjacent images is 250 seconds.

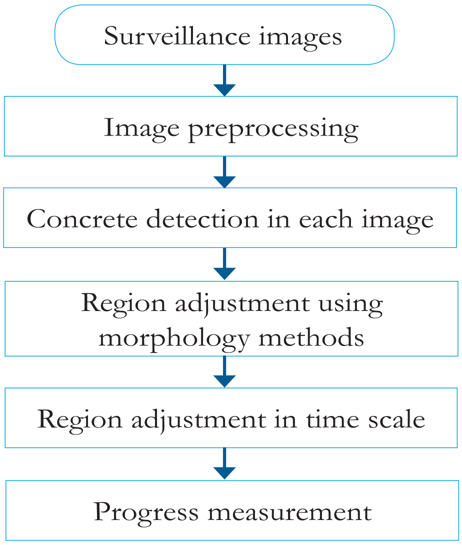

Figure 2 The Flowchart of the Analysis Method

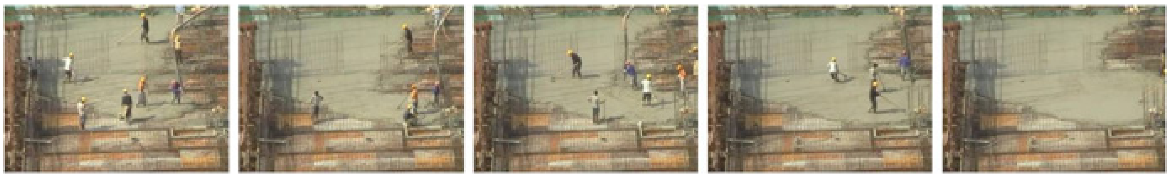

Figure 3 The Five Testing Image Frames

(a) Original Image **(b)** The Result of Preprocessing

Figure 4 The Result of Image Preprocessing of the First Testing Image

Figure 5 Extracted Concrete Region in the Testing Images

Figure 6 Results of Morphology Options in a Single Frame

Figure 7 Results after Adjustment in Time Scale

Figure 8 The Concrete Region Taken Off Manually

Table 1 The Areas of Extracted Cement Concrete Region

	Image 1	Image 2	Image 3	Image 4	Image 5
Areas in Fig 7 (px)	193995	203916	220286	240494	250234
Increasing area (px)	-------	9921	16370	20208	9740
Areas in Fig 8 (px)	158148	164011	178121	192881	194390
Increasing area (px)	-------	5863	14110	14760	1509

Figure 4 shows the result of image preprocessing. The reinforcing steel in the testing image was removed after preprocessing and the shadows of workers and on-site objects were diminished as well. The image after preprocessing is lighter and blurrier than the original one, which is the consequent effect of image spatial filtering.

Figure 5 shows the results of concrete region extraction, which is the third step in the flow chart shown in Figure 2. As can be noticed, the extracted concrete region is disconnected in some places. This is mainly caused by on-site workers and their shadows, which significantly differ from the cement region in color and texture.

The image morphology options can be employed to deal with the region discrete problem as mentioned above. Figure 6 indicates the results of morphology operations. We can see that the primary concrete region was extracted and connected as a flat region.

As described in section 2, concrete work in civil construction is usually irrevocable. This means that one location will remain in concrete region once it was completed. We can reshape the concrete region extracted from a single image frame according to the former extracted regions. Figure 7 shows the reshaped concrete regions in testing images.

Figure 8 shows the cement regions which are measured manually under a very strict rule. Apparently, each region in Figure 7 differs with the corresponding region in Figure 8 to a certain extent. The region in Figure 7 is wider. This is because both the surrounding edges and the true cement regions have a relatively similar color and texture range. This makes the automatic region extraction indistinguishable. Besides, the manual option is highly subjective. This may also contribute to the difference between the manual and automatic results.

Table 1 provides the specific areas of each extracted regions in Figure 7 and Figure 8. The measurement of the area is pixel. The increasing area can also be calculated from the given areas. The unit “px” is the abbreviation of pixel. The mean error of increasing areas in Figure 7 and Figure 8 is 5000px. The presented method could extract finished cement concrete region to a certain degree. The results of the progress are exaggerated, but show similar trend with the manual demarcation.

CONCLUSION

Progress measurement is an important component in productivity assessment. The accurate measurement of work in progress on construction sites is vital for productivity assessment, which can be further used for project time and cost control. This paper uses concrete work as an example to research progress measurement using image processing method. The experiment shows that the proposed method can extract the completed concrete region in the image frames with a certain level of accuracy.

The future work of concrete progress measurement will focus on two issues. The first one will be the actual area calculation based on the parameters of camera, such as location and angle. The second one is to compare the result with manual test data. The results of the progress measurement can be used for productivity assessment.

ACKNOWLEDGEMENT

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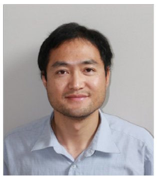


Dr. Yuhong Wang received his bachelor degree in construction management engineering at Tongji University in China in 1996. He worked for a construction consulting firm in Shanghai in 1997, before entering the master degree program in project management at Tongji University. Dr. Wang received his master and Ph.D. degree in Civil Engineering from University of Kentucky. He worked for two years at Kentucky Transportation Center as a research engineer, another two years as Assistant Professor in Civil Engineering Department at Lawrence Tech. University, followed by another three years as an Assistant Professor in the Construction Management Department at East Carolina University. Dr. Wang is a registered professional engineer in Kentucky, U.S. (Registration No. 23736). Dr. Wang has been a PI or key researcher on more than 20 research grants sponsored by various Hong Kong, U.S., and international agencies. The total amount of these grants is over 3 million US dollars. In addition, Dr. Wang has published more than 40 refereed papers, book chapters, and research reports. Dr. Wang's research interests include construction productivity, safety and health.

Dr. Chichun Hu is an Associate Professor from College of Civil and Transportation Engineering, South China University of Technology. His research interest focuses on pavement engineering and digital imaging analysis. He is currently working on "Three Dimensional Digital Design of Asphalt Mixture based on X-ray Computed Tomography" sponsored by National Natural Science Foundation of China.

Chen Ling is a Ph.D. student specialised in image processing and pattern recognition. Before being admitted to the Ph.D. programme, she worked as a research assistant in the Department of Civil and Environment Engineering in the Hong Kong Polytechnic University after graduation from Sun Yat-sen University with a master degree. She currently works on the research topic of construction productivity and safety analysis based on video understanding.

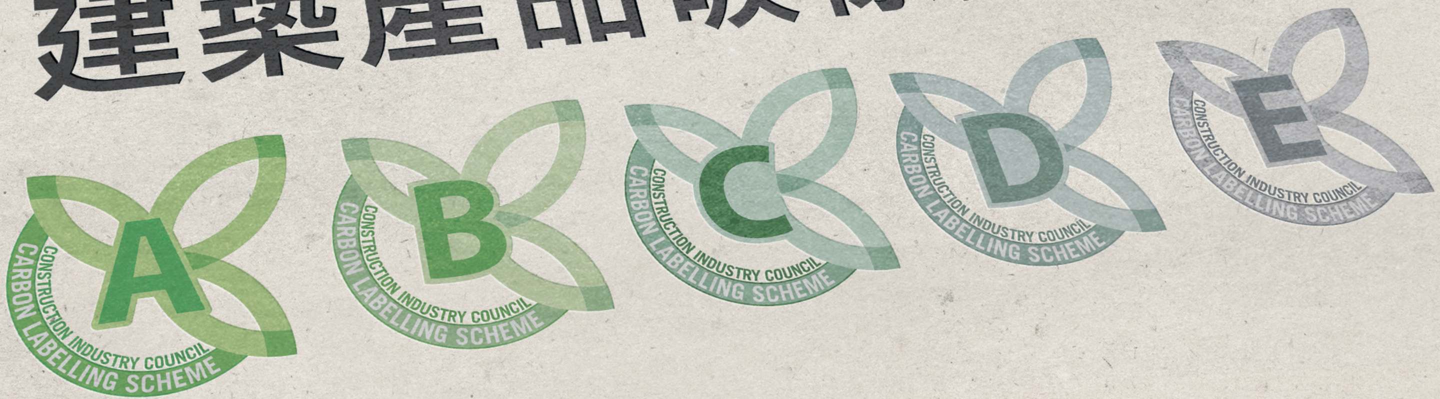
Research Title	Development of High Modulus Concrete for Tall Buildings	Innovative Design Technique for Steel-concrete Composite Structures in HK	Adopting Eurocodes by HK Construction Industry Technical Guide on Effective Design and Construction to European Steel Code	Formulation of Sustainable Trigeneration System Design for High-rise Commercial Buildings in HK	s-Helmet: A Proactive Construction Safety Management System based on Real-time Localisation	Development of an Automatic Image Collection and Analysis System for Improving Onsite Construction Productivity
Principal Investigator	Prof. Z.L. LI (HKUST)	Prof. S.L. CHAN (HKPolyU)	Prof. K.F. CHUNG (HKPolyU)	Dr. K.F. Square FONG (CityU)	Prof. J.N. CAO (HKPolyU)	Dr. Y.H. WANG (HKPolyU)
Brief Description	Aims to develop high modulus concrete with sufficient comprehensive strength and toughness for tall building construction.	To develop an approach for more efficient and cost-effective design of more ductile composite structures where steel members are directly encased inside concrete to produce a form of steel-concrete composite.	To compile a technical guide to promote the effective design and construction of steel structures to BS EN 1993-1-1 (Eurocode 3: Part1), to HK design and construction engineers, aiming to facilitate adoption Eurocodes by Hong Kong Construction Industry.	Aims to formulate the sustainable trigeneration system design for high-rise commercial buildings in HK, by modeling different trigeneration configurations, surveying up-to-date information of energy, environmental and economic analysis.	To develop a proactive construction safety management system called s-Helmet, which is able to continuously monitor workers' locations and automatically issue warning alarm when they are near to danger zones.	To develop an automatic image collection and analysis system that collects onsite work progress information, processes the images and generates the productivity report, aiming to improve the construction productivity.
Key Deliverables	1. Optimised mix for high modulus concrete 2. Influence test on reinforcement 3. Application of high modulus concrete in structure members 4. Research papers	1. An advanced and new design method for steel-concrete composite structure 2. Research publications 3. Relevant seminars	1. A technical guide 2. Technical content and support to CIC for webpage based technical platform for Eurocode 3 3. An international symposium in HK on Eurocode 3 adoption	1. A design of sustainable trigeneration system 2. Evaluation on the trigeneration design 3. Guidelines on sustainable trigeneration design 4. Research papers	1. The s-Helmet which consists of an onsite localisation subsystem and a remote management sub-system 2. Research papers 3. Relevant patents	1. An automatic workface productivity and measurement and analysis system 2. Application of the system to real construction situations. 3. Research papers
Guideline / Patent	Y	Y	Y	Y	Y	Y

CONTRIBUTION TABLE

CONSTRUCTION INDUSTRY COUNCIL
建造業議會

ZCB
零碳天地

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

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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