CONSTRUCTION INDUSTRY COUNCIL | INNOVATION IN CONSTRUCTION

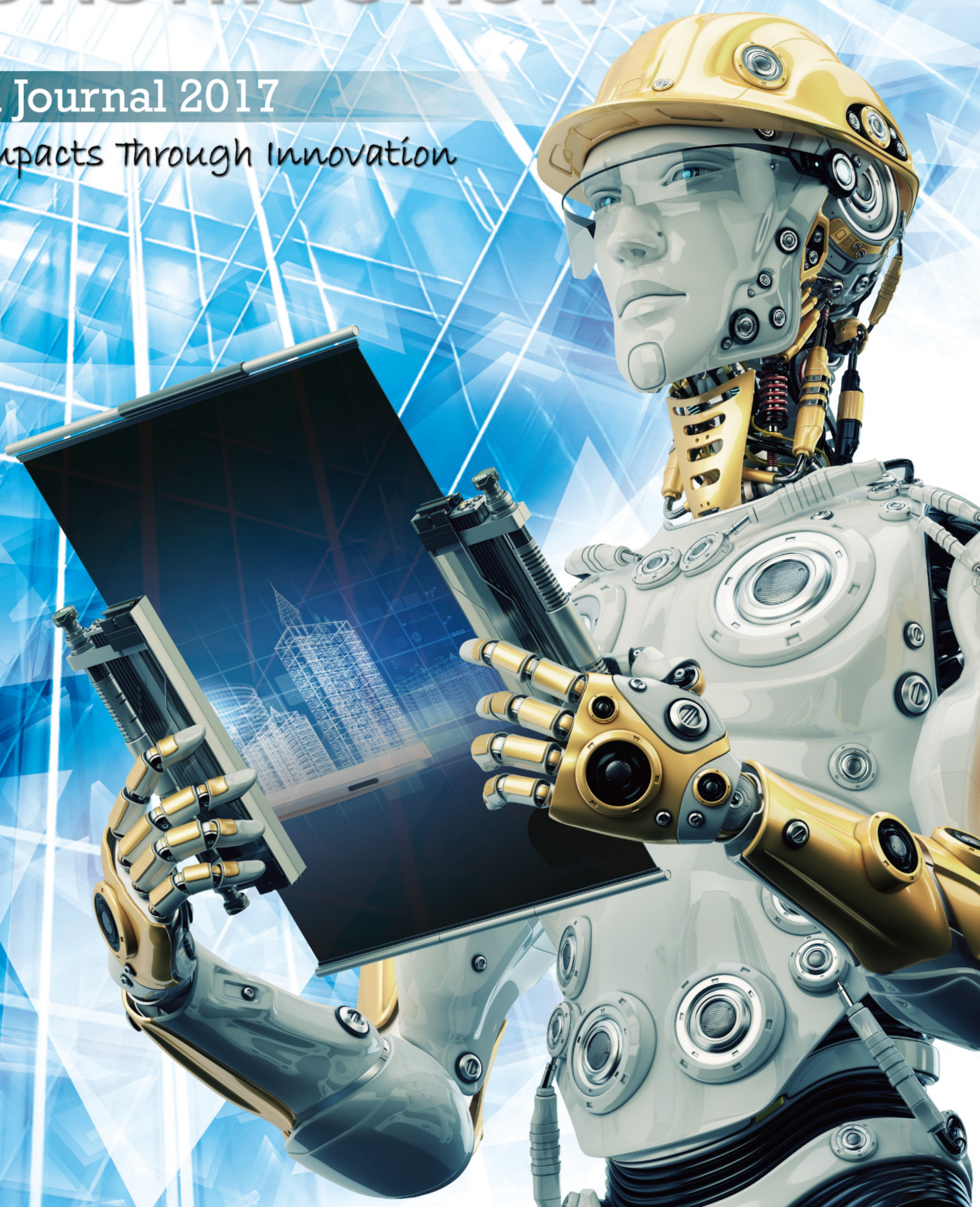
iCON | THIRD ISSUE

CONSTRUCTION
INDUSTRY COUNCIL
建造業議會

# INNOVATION in CONSTRUCTION

## Research Journal 2017

*Creating Impacts Through Innovation*



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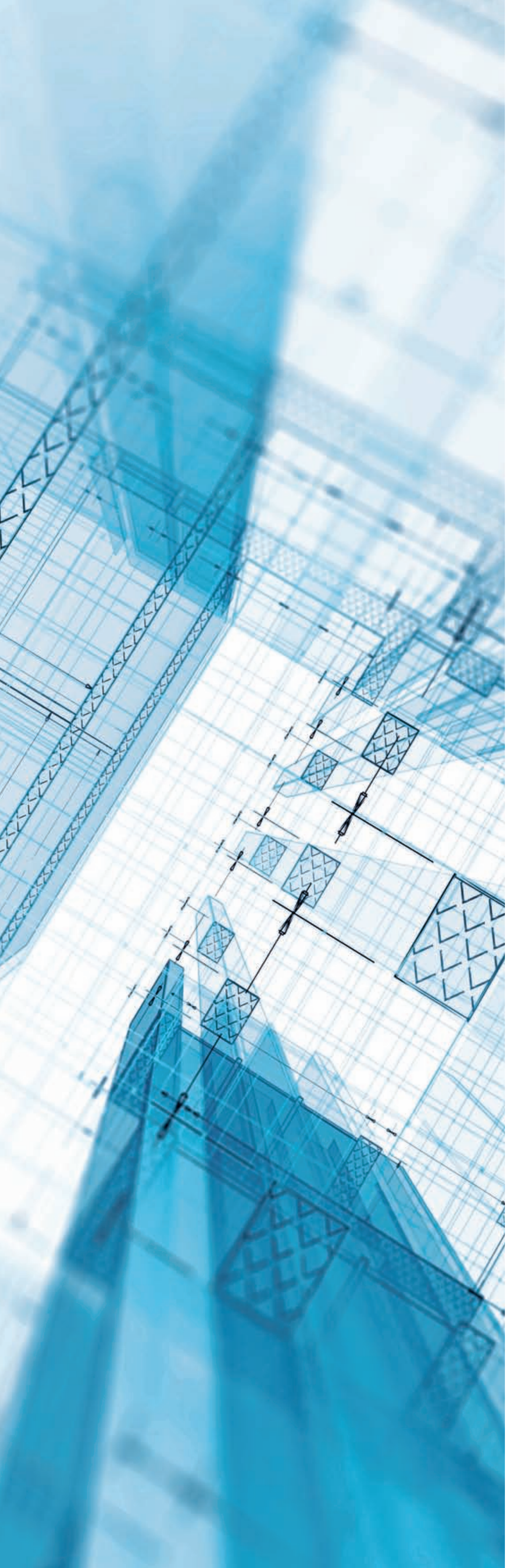

# INNOVATION IN CONSTRUCTION

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# CONTENTS

## ABOUT CONSTRUCTION INDUSTRY COUNCIL

The Construction Industry Council (the CIC) was formed on 1 February 2007. The 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 the 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, the 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.

The 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.cic.hk.

## VISION

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

## MISSION

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

# EXECUTIVE DIRECTOR'S MESSAGE

Hong Kong has been ranked as the world's champion in infrastructure for seven consecutive years in the Global Competitiveness Report 2016-17 published by the World Economic Forum, reflecting Hong Kong's outstanding achievement in the provision of its infrastructure facilities. Construction Industry Council (the CIC) has predicted that the overall output in the construction industry would be more than HK$200 billion in the coming years. Without doubt, the construction industry is booming.

We see "opportunities and threats". While Hong Kong's construction industry is in a golden era, we face construction manpower shortage, high construction cost, the need for enhancing sustainable construction process and construction site safety. Our opportunities and challenges lie in innovating our construction process and methodology which can maintain quality on the one hand and improve sustainability, productivity, and safety on the other. With continuing advancement in science and technology, opportunities are abundant for us to think out of the box of our conventional construction methods. Here, designers, builders, contractors, and sub-contractors and workers too have an important role to play and contribute.

The CIC, representing key stakeholders of the construction industry, has all along strived to support the research and development of new technology and serve as a platform between the research community and the construction industry to innovate. Through the CIC Research Fund set up in 2012, The CIC has funded research institutions on undertaking over thirty projects in the areas closely connected to the industry.

"*Innovation in Construction (iCON)*" is a research journal for industry practitioners to be informed and to report abreast of latest research findings which would form a basis for us to meet the challenges. We welcome your comments on the findings and suggestions for any research items which you think from your own experience and exposure would benefit the industry.

I would like to give my appreciation to the efforts made by the researchers of the funded projects and my gratitude to the Chairman, Mr. Jimmy TSE, and members of the Task Force on Research of the CIC who have been working hard with the researchers and preparing iCON.

For the future, we will continue to provide financial support to research institutes to carry out research which meet the challenges of the industry.

**Mr. CHEUNG Hau-wai**
*Executive Director*
Construction Industry Council

# EDITORIAL

**Jimmy TSE, MH**
*Chief Editor*
Chairman, Task Force on Research
Construction Industry Council

The Task Force on Research of the CIC, is tasked to encourage research activities and the use of innovative techniques and, to establish or promote the establishment of standards for the construction industry. We publish the journal of "Innovation in Construction" (iCON) to provide a knowledge sharing platform where researchers can disseminate their latest findings in construction and facilitate industry practitioners to tap the latest finding of leading researchers in innovative construction techniques.

The emphasis of iCON is on innovation in aspects of information technology, new technology and materials, process control and project management. On behalf of the Task Force, I am pleased to introduce you in this issue of iCON, the most updated and inspiring research findings in four projects supported by the CIC Research Fund.

First of all, I would like to express my very sincere gratitude to Professor Thomas BOCK, an expert in building realization and robotics at the Technical University of Munich, who will share his experience in the application of construction automation in this issue. He enlightens us the potentials of implementing robotics and automation in Hong Kong's construction industry.

We are also indebted to the researchers and authors who have contributed four other articles to this Journal. In this issue, we have three research articles dedicating to improve the construction safety. Professor A.Y.T. LEUNG designs a stablilizer through integration of electrical and mechanical (E&M) gyroscopes and compressed air ejectors, which serves as prototype system for improving site safety of tower cranes and gondolas. Professor F. K.W.WONG identifies underlying causes of E&M works related accidents in Hong Kong and provides practical recommendations to improve safety and health of E&M practitioners. Professor H. LI proposes a real-time motion system for detection of risk postures and prevention of construction workers' work-related musculoskeletal disorders through alarm warning. Besides, we have a research article on enhancing the use of sustainable construction materials. A project team consisting of Dr. M.L. SHAM, Professor C.K.Y. LEUNG and Professor K. Shih develops a waterproofing rendering made of engineered cementitious composites to address the water seepage buildings in Hong Kong. As a next step, riding on the research findings, we shall liaise with the industry to put the thought and innovations to practical use.

We are pleased to learn that iCON has served to facilitate research institutions to unveil innovative ideas and advice for industry development. I can assure you that we will continue our work to turn new ideas to reality. Your feedback on iCON and the work of our Task Force is always welcome. Let's join hands in moving the construction industry forward through innovation.

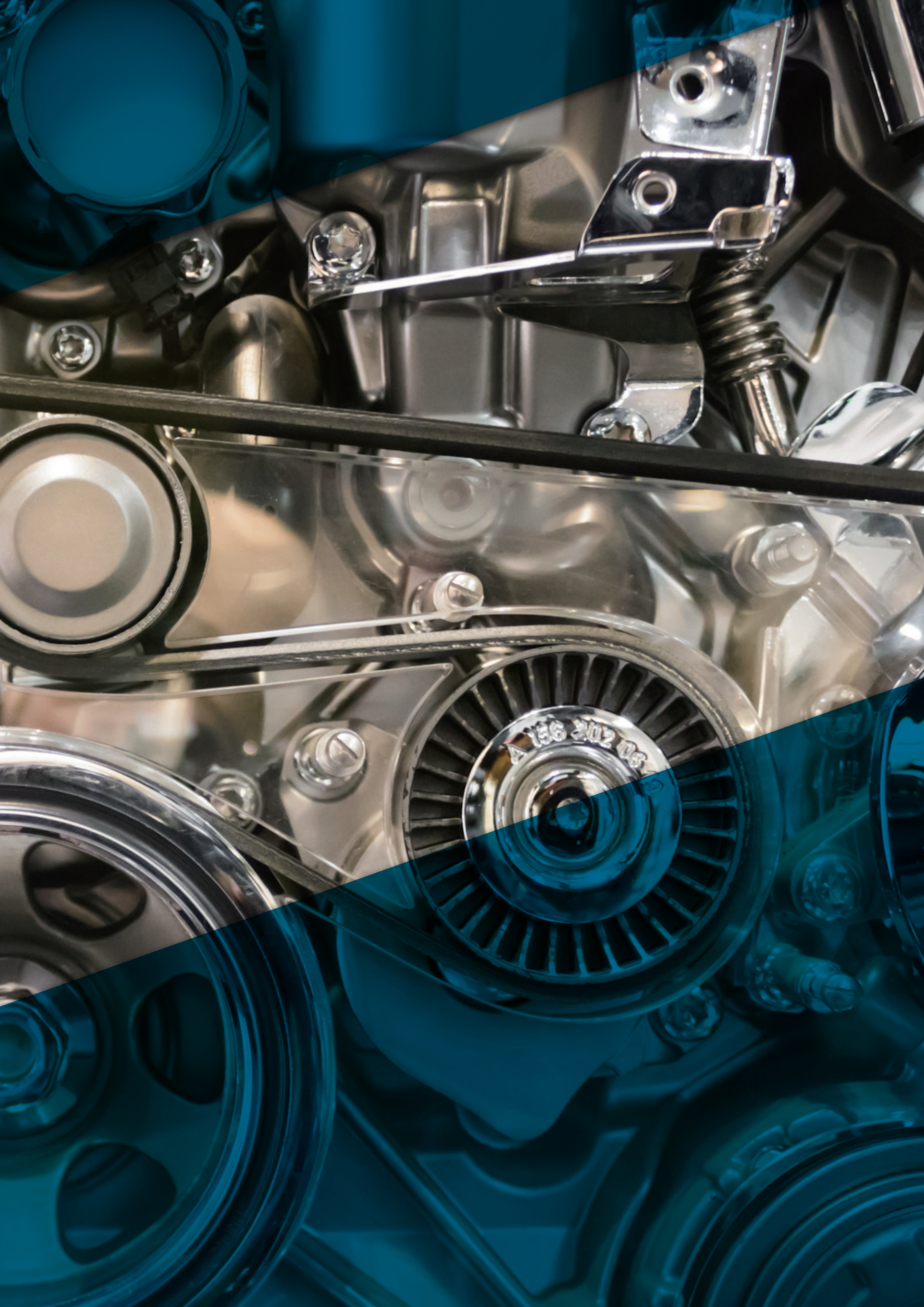
# Introduction of CIC Research Fund

The Construction Industry Council (the CIC) was formed on 1 February 2007 in accordance with the Construction Industry Council Ordinance (Cap. 587). The CIC encourages research projects that are directly related to the needs of the industry. Under the Ordinance, one of the main functions of the 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.

The CIC from time-to-time initiates research projects to meet the industry needs. These research projects initiated by the 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.

The CIC also supports research projects initiated by Research Institutes which aim to benefit the local construction industry through practical application of the research outcomes. The research projects with high potential to obtain the 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.

# Expert Interview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# EXCLUSIVE INTERVIEW WITH AN INDUSTRY VISIONARY

**Professor Thomas BOCK**
*Chair of Building Realization and Robotics*
Department of Architecture
Technical University of Munich

Prof. Thomas BOCK is a Professor of Building Realisation and Robotics at Technical University of Munich (TUM), Germany. He has 35 years' research experience in automation and robotics in building construction, and has placed focus on this subject from planning, prefabrication, on-site production and utilization phases to the reorganisation and deconstruction of a building. He is member of boards of directors of many international associations and international academies in Europe, Americas, and Asia. He has exchanged ideas with international ministries and has evaluated research projects for international funding institutions. He holds qualifications of honorary doctor, professorship degrees and visiting professorships. Prof. BOCK heads various working commission and groups of international research organisations, serves on several editorial boards and has authored and co-authored about 450 articles. He co-authors a 5 volumes publication series entitled "The Cambridge University Press Handbook on Construction Robotics".

The Hong Kong construction industry is internationally renowned for its expertise in constructing quality high-rise buildings and mega-infrastructure. Facing the changing market requirements and fierce competition among global players, the emergence of automation and robotics brings us possible solution to enhance productivity with a view to sustaining its competitiveness. The CIC seized a valuable opportunity to carry out an exclusive interview with Prof. BOCK to reveal his views and insights to tackle the challenges we are facing.

## The Robotic Era

*"The end of the information age will coincide with the beginning of the robot age. However, we will not soon see a world in which humans and androids walk the streets together, like in movies or cartoons; instead, information technology and robotics will gradually fuse so that people will likely only notice when robot technology is already in use in various locations." Hiroshi Ishiguro (2012)*

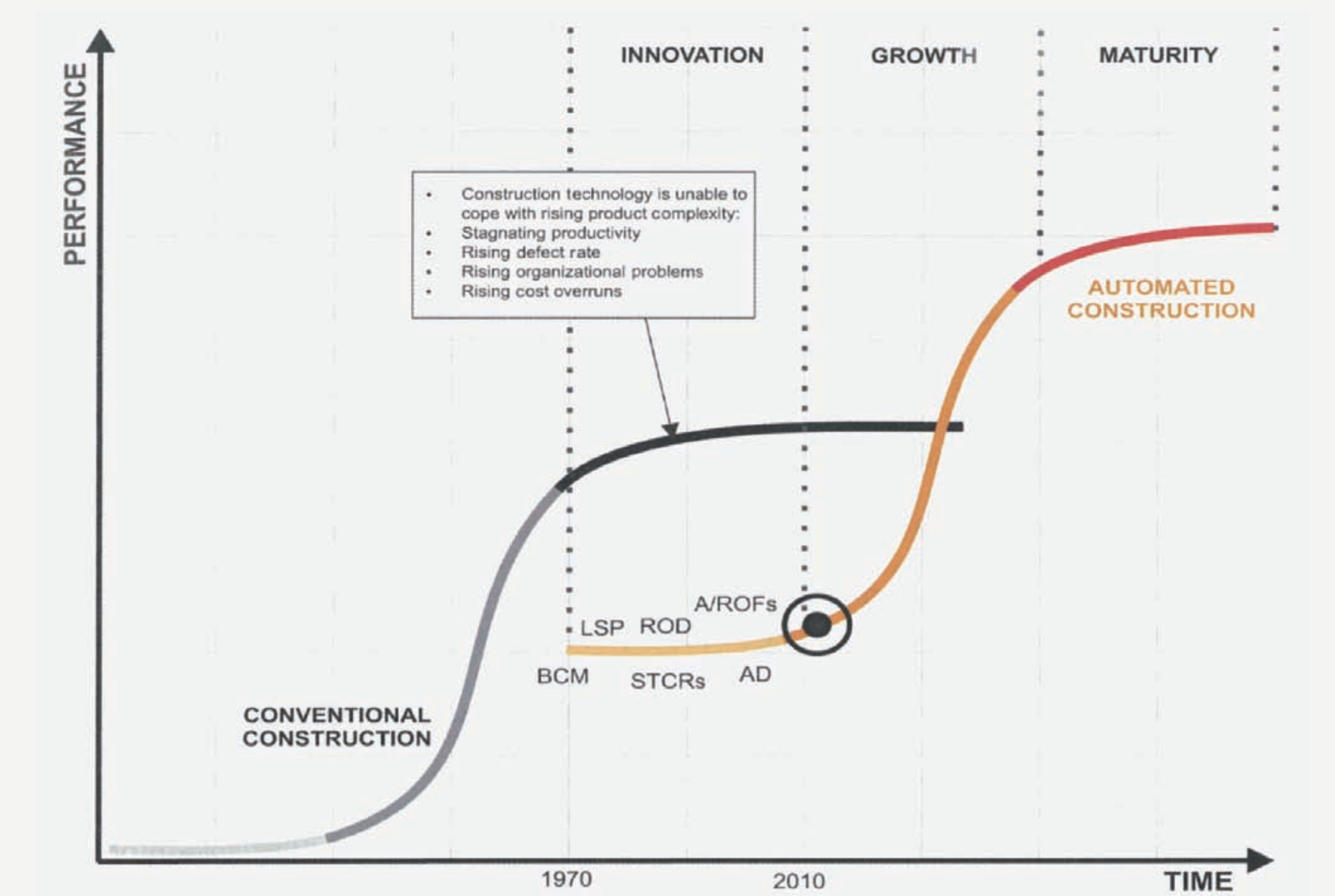
This quotation of Hiroshi Ishiguro, the mastermind who is notable for the development of the well-known Japanese android Repliee Q1Expo, appears in the very beginning of Professor Thomas BOCK's Cambridge Handbooks on Construction Robotics series. The simple statement hits the nail on the head that the human civilisation has already entered the robotic era with almost imperceptible changes. Robotics has already been part of our daily lives without being aware by the majority. Nowadays, robots have been substantially improved; they become more user-friendly, less expensive, task adaptable, smaller, more widely distributed, and seamlessly integrated into work processes and devices. The benefits of advancement in robotic and automation can be identified in every corner of human activities e.g. electrical grid system, transportation system, traffic control, farming, food production, home and office automation, household robotics, manufacturing industry.

The development and adoption of robotic and automation distinguish dramatically across sectors. One rather lagged behind area with much room for development is robotics and automation in construction (RAC). Having said that, a number of the RAC applications have been implemented in both Hong Kong and overseas. Exoskeleton, which is worn by the workers, allows to lifting capacity up to 30 kilograms and it has been adopted on site for trial in a main contractor in Hong Kong; A robot for positioning of heavy reinforcing bars is developed to expedite reinforcing bar production and save on required labour for the task; An automatic climbing formwork is used to produce large reinforced concrete structures in a crane-independent manner; A facade painting robot improves the efficiency and accuracy as well as risk reduction of labours working at heights; A shuttle system for the installation of facade elements is introduced to eliminate the need for scaffoldings and cranes and it can be applied on inconvenient and dangerous working conditions; And a sky factory, consisted of a self-climbing temporary roof and a parallel material delivery system, is the first automated construction system which improved overall productivity.

"RAC still has ample room for improvement", firmly anticipated by Prof. BOCK. It is a golden time for the Hong Kong construction industry, which is facing the challenges of labour shortage and huge construction demand, to adopt RAC.

## The Challenges ahead of Adopting Robotics and Automation in Construction

Prof. BOCK explained that development or performance of every newborn technology over time can be described in form of S-curve. In his Cambridge Handbooks on Construction Robotics series, the S-curve can be divided into 3 phases, representing the life cycle of RAC development.




*Source: Bock, T., Linner, T., 2015, Robot-oriented Design, The Cambridge Handbooks on Construction Robotics, The Cambridge University Press*

The Innovation Phase describes the infant stage of RAC where there was very limited knowledge in the field and extensive amount of R&D spending with relatively low or no outcome. In this stage, the developed prototypes are unlikely to commercialise. In the Growth Phase, RAC knowledge essentially increases and the technical and organizational obstacles can be broken though; there is rapid growth in the adoption by users and commercialisation. In the Maturity Phase, the RAC technology has been widely used but enters a lag of further enhancement.

The performance of new technologies in RAC at their initiation and early development may be lower than that of conventional construction and practices. While it provides less confidence and uncertainties to the users at the beginning, it will gradually improve in terms of performance and popularity. "RAC is at the beginning stage of the Growth Phase in Hong Kong. Conventional construction still dominates in the industry. The stagnations are very alike for the development of every fresh technology or product. With observation of the advancement in the robot technology, I believe that it will experience a rapid development similar to that of the personal computer during the 1990s", Prof. BOCK pointed out.

When looking at the hurdles of RAC development in Hong Kong, "Hong Kong's building construction is featured with numbers of unique characteristics among the developed megacities around the world" said Professor BOCK. Hong Kong has the largest density of high-rises and skyscrapers; Hong Kong is also well known for its challenging site conditions i.e. sites by sea, sites in mountain area, and sites in crowded urban area. Apart from the technical challenges ahead, more importantly, there are institutional factors confronted by the industry such as insufficient demand pull from private developers/clients, overwhelming regulatory and administrative restrictions on construction, lack of a supportive research structure, insufficient attention paid to optimizing buildability and standardisation in the design stage. Prof. BOCK pointed out that RAC must be cultivated and developed in the economically, politically and technologically ready environment.

## The Action forward: Robot-oriented Design & Process Re-engineering

The core of RAC technique is fundamentally the reformation of construction process, also known as construction process re-engineering. The concept of robot-orientated design (ROD) was first introduced in 1998 by Prof. BOCK and it served later as the basis for RAC and other robot-based applications. "ROD is concerned with the co-adaptation of construction products and automated or robotic technology, so that the use of such technology becomes applicable, simpler, or more efficient", said Prof. BOCK.

"It is delightful to see that Hong Kong has made groundbreaking achievement in the precast building element, standardisation and modular design, which are important approaches towards ROD." said Prof. BOCK. The first major technology reform was the introduction of large panel steel formwork into the public housing construction in Hong Kong in the 1970s, and after that, the precast concrete construction was adopted in public housing in the 1980s. Now, precast construction is being promoted to different building and infrastructure works.

Modular flat design for public housing development could further improve the performance of construction time, cost, quality, safety and etc. Large-scale bar cutting and bending factories were erected in Tsing Yi recently. It pioneered offsite rebar cutting and bending in Hong Kong and could improve site safety, production quality and cost-effectiveness of steel fixing works. It provides valuable experience to prefabrication construction in Hong Kong. Radio frequency identification (RFID) tag chip-based process control and monitoring are also another achievement made by Hong Kong Housing Authority in recent years. It helps logistic control of precast products from manufacturing, transportation and construction.

"ROD should not only be applied for construction stage of buildings but also for the entire life cycle of buildings i.e. maintenance, renovation, and deconstruction to achieve full-scale RAC", suggested by Prof. BOCK. "The construction industry must reinvent itself to adapt the new situation."

## Joint Forces for Attaining Transformation

"Hong Kong has never lacked for construction talents and expertise, some of which are undoubtedly world-class as we could witness from the continuous export of our capabilities to Mainland China, Southeast Asia, and other territories. Yet, there is apparently a bottleneck in exploiting the synergies among different professionals in terms of upgrading the industry's productivity", stated by Prof. BOCK.

Advocating the benefit of standardisation and modular design is the first action to be taken in achieving RAC. Given that the public building sector in Hong Kong has already taken initiatives towards standardisation and modular design, the next challenges are how to motivate private developers/clients and better structuring local supportive researches. Prof. BOCK was aware that the readiness of other industry stakeholders is of great importance. He stressed, the developers should be the driving force of leading the application of RAC in Hong Kong while different sectors of the industry i.e. designers, constructors, manufacturers, academia, and the Government, play different but significant roles in transforming the modernity to another level.

He noted that the CIC has all along encouraged research activities for industry development. He opined that, to better utilise the RAC to fulfil the needs of the industry, it is imperative to have close collaboration between funding agencies, research institutes and the industry practitioners so as to produce the down-to-earth research findings.

## *Postscript*

*Educated in Germany, USA and Japan, working in Europe, Iran, America and Japan, and now being a leading researcher in the Technical University of Munich, Professor Thomas BOCK witnessed many of the epoch-making moments of the evolution of RAC. His savvy in RAC and far-sighted vision provides us with a thorough review and future direction of RAC. In the mission of enhancing the productivity, safety and health, sustainability, as well as improving the "attractiveness" of the construction industry in Hong Kong, CIC has initiated a consultancy project with Professor BOCK in 2016 namely "**Investigating the Potentials of Implementing Robotics and Automation in the Context of Large-scale Housing Development for Hong Kong**" aiming to identify opportunities and determine the optimal tradeoff between standardization and individualization so that highly productive housing manufacturing system can serve the needs of large variety of housing typologies in Hong Kong. The CIC looks forward to the outcomes of the study and believes with the joint forces of all construction practitioners the RAC will be fully stretched in Hong Kong.*

# A Hybrid Gyroscopic Stabilizer for Construction Tower Cranes and Gondolas Under Environmental Wind

# A HYBRID GYROSCOPIC STABILIZER FOR CONSTRUCTION TOWER CRANES AND GONDOLAS UNDER ENVIRONMENTAL WIND

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**ABSTRACT**
Tower cranes and gondolas are widely used in construction projects for their load carrying capacity. However, these plants pose significant safety hazards to operation personnel from sway caused by load hoisting and environmental wind. To mitigate such safety hazards, we propose a control mechanism that combines both electronic and mechanical gyroscopes to produce a balancing torque and stabilize the crane load. In order to achieve this goal, a prototype stabilizer has been developed and its performance was examined in wind tunnel tests. The final design of the hybrid gyroscopic stabilizer utilizes the electronic gyroscope to track the real-time position and orientation of payload and adjusts the torque with air ejectors to counter balance the sway so that the amplitudes of oscillation can be quickly reduced.

**Key words:** Hybrid control mechanism; environment wind; oscillation; mechanical and electrical gyroscope



## INTRODUCTION

Tower cranes and gondolas are widely used construction plant. For example, tower cranes are required to lift prefabricated building components and materials to precise locations in high construction speed. Owing to their high installation height, they inevitably withstand payload sway caused by environmental wind. These sways pose a significant safety risk to operational personnel. When tower cranes and gondolas are subject to over torques and heavy load under strong wind, it is extremely difficult to maneuver their supporting structures and hoisting lines. In general, when the wind speed exceeds 20 m/s, all tower crane operation must be halted (Winn *et al*., 2005). Any undesired movement of crane load will also reduce the construction efficiency and prolong the schedule. A crane operator can suppress such movement by slowly moving the trolley with small increments, but it dramatically degrades efficiency and throughput. Besides, the uncertain disturbance caused by environmental wind will pose impact on the operation. To resolve this problem, many researchers focus on improving control systems of tower cranes, such as neural-networks-based anti-sway control approach (Abe, 2011), motion planning-based adaptive control method for cranes (Fang *et al*., 2012) and Takagi-Sugeno (T-S) fuzzy-model-based state-feedback controller (Zhao and Gao, 2012). In this paper, we propose to utilize a hybrid gyroscopic stabilizer to automatically reduce the sway intensity.

In order to minimize the undesired sway, this paper aims to develop a stabilizer with proper control mechanisms. The oscillation of crane load and hoisting system is assumed as an inverted pendulum with (1) rigging connection between trolley and hook and (2) cable link between hook and payload based on previous study of passive control of convey cranes (Collado *et al*., 2000). Combining both electrical and mechanical gyroscopes, prototype stabilizers were developed for in-lab test. The final control mechanism was examined by a small wind tunnel and simulation. The swing angular velocity, swing angular acceleration, payload position velocity, and payload position acceleration were reported to validate the findings.

## PENDULUM-TYPE HOISTING SYSTEM AND SIMULATION SETUP

The hoisting system of a tower crane consists of trolley, hook and payload. These three parts are connected with each other by riggings. When modelling crane dynamics, the lumped-mass and distributed parameter system are most widely used (Hong and Ngo, 2009). In lumped-mass system, hoisting rope is modelled as a mass-less rigid rod and the payload is modelled as a lumped point mass; while in the distributed parameter system, the hoisting rope is considered as a string. Under both assumptions, the overhead crane model behaves like a pendulum (Chang *et al*., 2012). For natural sway, there is no obvious difference between payload mass and hook mass. Under some conditions, such as the riggings between hook and payload is long and tow cascaded payloads are carried together, the tower crane behaves like a double pendulum. The double-pendulum dynamic is more complicated, given its double natural frequencies degrade the effectiveness of controllers. Controlling double pendulum type cranes require coupling non-linearity and dynamic motions of trolley, hook and payload. Therefore, the control system proposed in this paper focuses on passive control and models the hoisting system as an inverted pendulum. For the inverted pendulum-type hoisting system, we assume following characteristics to simulate the control algorithms' performance under various environmental wind:

- Comparing to the riggings between trolley and hook, the riggings between hook and payload is short. The payload and the hook are connected by a rigid hollow rod.
- The swing angular velocity and acceleration of rod and the position velocity and acceleration of payload are measurable.
- The mass and the length of the connecting rod are known.
- The ball joint that connects the payload link to the rod is frictionless and does not rotate.
- The movement of the payload is restricted to one direction.

Based on above assumptions, the dynamic of the hoisting system can be explicitly presented by following motion equations. The length of the distance between trolley and hook is $l$, and the weight of payload is $m$. The angular displacement along the vertical direction is $\theta$. The drag force of payload is in proportion to the speed of itself. Damping coefficient is $r$. The payload is acted upon by a force $F$, which is a continuous force with the cycle $\omega_d$.

$$ml\frac{d^2\theta}{dt^2} + rl\frac{d\theta}{dt} + mg\sin\theta = Fcos\omega_d t \quad (1)$$

$$\frac{d^2\theta}{dt^2} + \frac{r}{m}\frac{d\theta}{dt} + \frac{g}{l}\sin\theta = \frac{F}{ml}cos\omega_d t \quad (2)$$

We introduce $\omega_0 = \sqrt{g/l}$, $m\omega_0^2$, $ml\omega_0^2$ to substitute the motion dimensions. The variables in the equation can be rewritten as $\beta = r/2m\omega_0$, $f = F/ml\omega_0^2 = F/mg$, $\omega_0/\omega_0 = 1$, $\omega = \omega_d/\omega_0$ for simplification. Then the new dimensionless differential equations of the motion of hoisting system can be written as,

$$\frac{d^2\theta}{dt^2} + 2\beta\frac{d\theta}{dt} + \mathrm{s}\sin\theta = fcos\omega t \quad (3)$$

Under deterministic wind load, the boundary condition will have $f \neq 0$. The sway of hoisting system enters a state of chaos. In order to constitute three-dimensional phase space, we put above equation into three differential equations,

$$\begin{cases} \dfrac{d\theta}{dt} = p \\ \dfrac{dp}{dt} = -2\beta\dfrac{d\theta}{dt} - sin\theta + fcos\omega t \\ \dfrac{d\varphi}{dt} = \omega \end{cases} \quad (4)$$

$\theta$, $p$, $\varphi$ are composed of three-dimensional phase space, in which phase angle $\varphi$ have a periodic character, then we do the plane connection between $2n\pi$ and $2(n+1)\pi$ and the

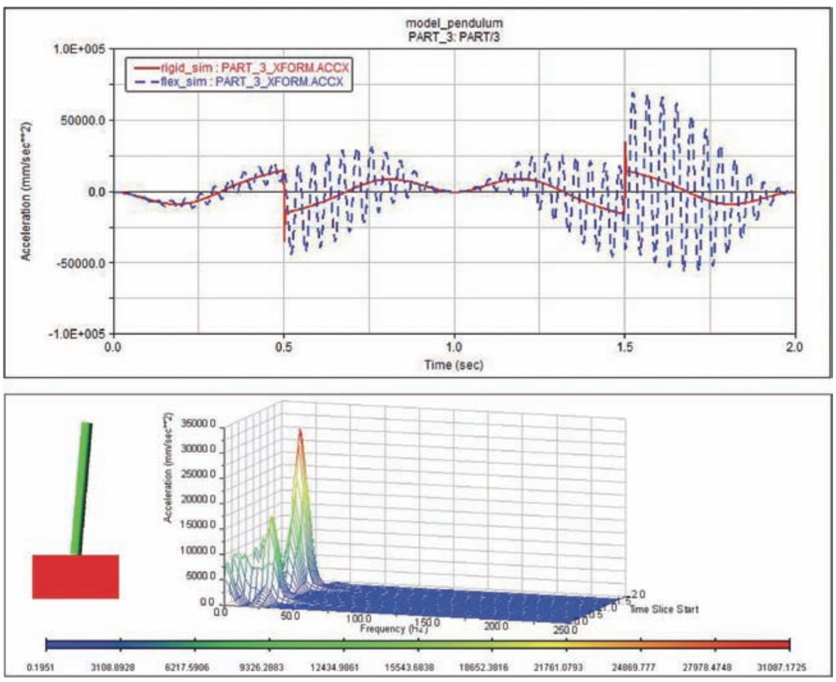


**Figure 1:** Sample simulation of the Pendulum-type hoisting system under environmental wind

phase space form a tyre tread. Since the sway of hoisting system enters into chaos, we conduct a simulation to have the visual dynamics result of pendulum-type hoisting system. To measure the dynamic of crane under external wind disturbance, the simulation model is created in MSC-ADAMS, a multibody dynamics simulation package, with four major variables of sway (swing angular velocity, swing angular acceleration, position velocity and position acceleration). To optimize the design of hybrid stabilizer, the control mechanisms will be tested in the simulation in future. Figure 1 shows a sample simulation trial with rotary inertia of 0.006kg.m$^2$ under wind load.

In the ideal construction environment without wind, the trend of velocity and acceleration of swaying angles are periodic; when considering wind, the velocity and acceleration of swaying angle is gradually changing due to the lateral dynamic load. So it is necessary to develop a control mechanism to automatically response to the changes.

## DEVELOPING HYBRID STABILIZER AND CONTROL MECHANISM

A suspender device with mechanical gyroscopes could automatically stabilize the load through rotation. However, a mechanical gyroscopic stabilizer that large enough for tower crane is extremely heavy to carry and requires large amount of energy to rotate. Therefore, low-cost, small size, and high accuracy electronic gyroscope is preferable (Nasir and Roth, 2012). In this paper, the mechanical and electrical gyroscopes are integrated to develop the prototypes of stabilizer. Figure 2 shows the design and control scheme of the stabilizer.

Two mechanical configurations of stabilizer are constructed for examination. Prototype 1 is a small scale stabilizer combines the mechanical and electrical gyroscopes with servo. The prototype 1 can stabilize the oscillation in one direction along the fitting gimbal direction. Then it is examined by a wind tunnel test to guide the future design. The prototype 2 (final design) are created based on results of the wind tunnel tests and simulation. Figure 3 shows the platform for the design of prototype 1.

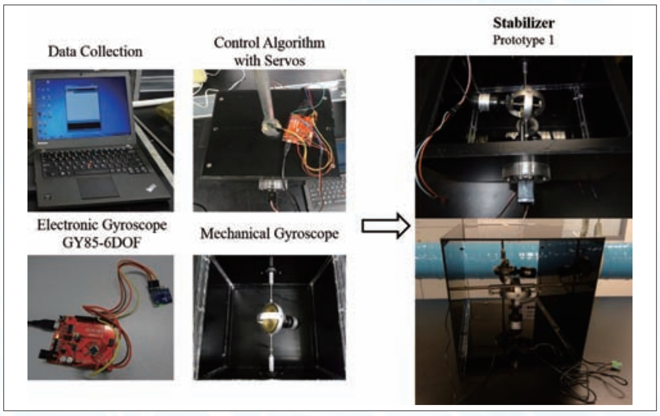


**Figure 3:** Configurations prototype 1 stabilizer

## VALIDATION AND RESULTS

In practice, the wind flow around a tower crane exhibits unexpected and complex aerodynamic properties. Therefore, we conduct an experiment with a scaled stabilizer (prototype 1) for construction crane under controllable wind. The experiment height that set between gyroscope and jib is 0.4m and the payload weight is 0.5kg. The apparatus of wind tunnel has an air outlet with a cross section of 0.4m by 0.4m and length of 4m, as shown in Figure 4.

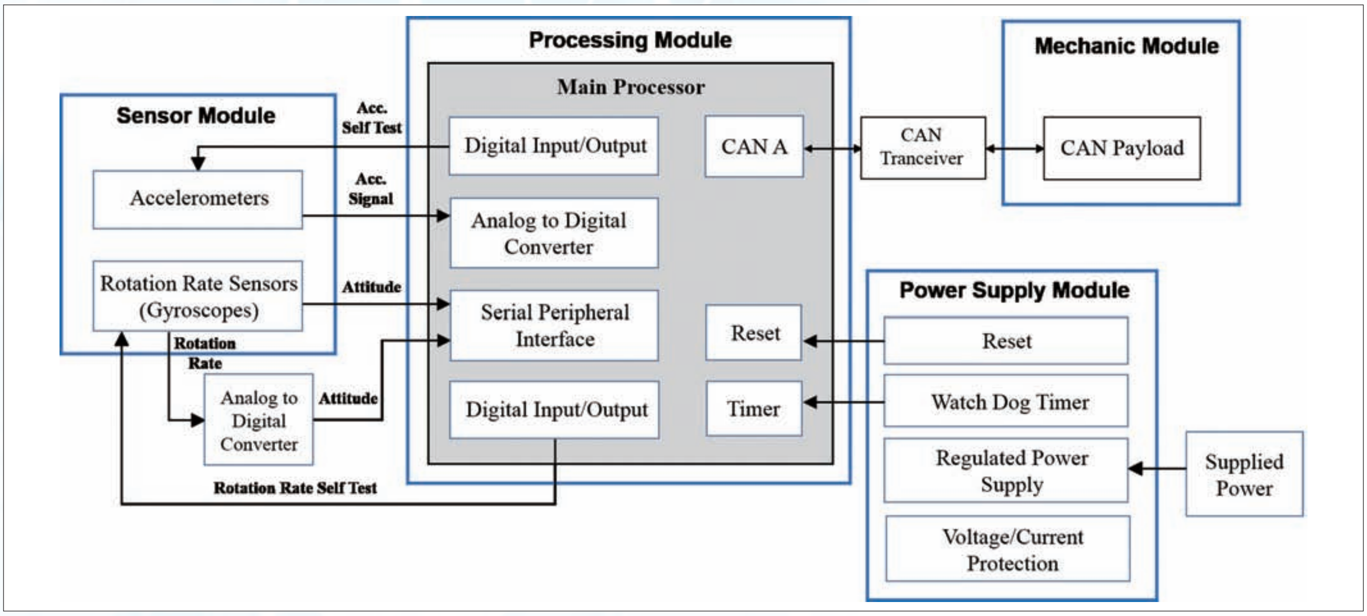


**Figure 2:** Design scheme of electrical stabilizer

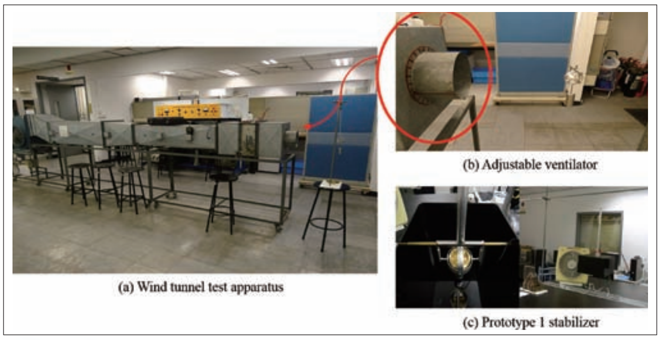


**Figure 4:** The apparatus of wind tunnel test

The initial position for stabilizer indicates the sway amplitude. The test includes the initial angle of 90°, 75°, 45° and 15°. The average wind speed in the experiment is 20.11m/s. The environmental temperature is 36.2°C. Wind pressure is 972.9mb and relative humidity is 18.6%. The total weight of stabilizer is 345g. The responding time of stop swaying is recorded to test the stabilizing efficiency. The settings of the environment wind are listed in the following Table 1.

**Table 1:** Environmental Wind and Position Orientation of Payload

| Time (sec) | Scalar Wind Speed (m/s) | Wind Direction (deg) | Swing Angular velocity (deg/s) | Swing Angular acceleration ($deg/s^2$) | Payload Position velocity x(m/s) | Payload Position acceleration x($m/s^2$) |
|---|---|---|---|---|---|---|
| 0 | 3.6 | 134 | -5.36 | -10.15 | 0.81 | -6.10 |
| 5 | 3.8 | 133 | -1.31 | -5.25 | 0.62 | 0.65 |
| 10 | 3 | 131 | -0.96 | 3.66 | 1.09 | 0.32 |
| 15 | 2.7 | 138 | -5.15 | 11.88 | 1.98 | 7.55 |
| 20 | 1.5 | 85 | 2.68 | 10.91 | 2.24 | 1.57 |

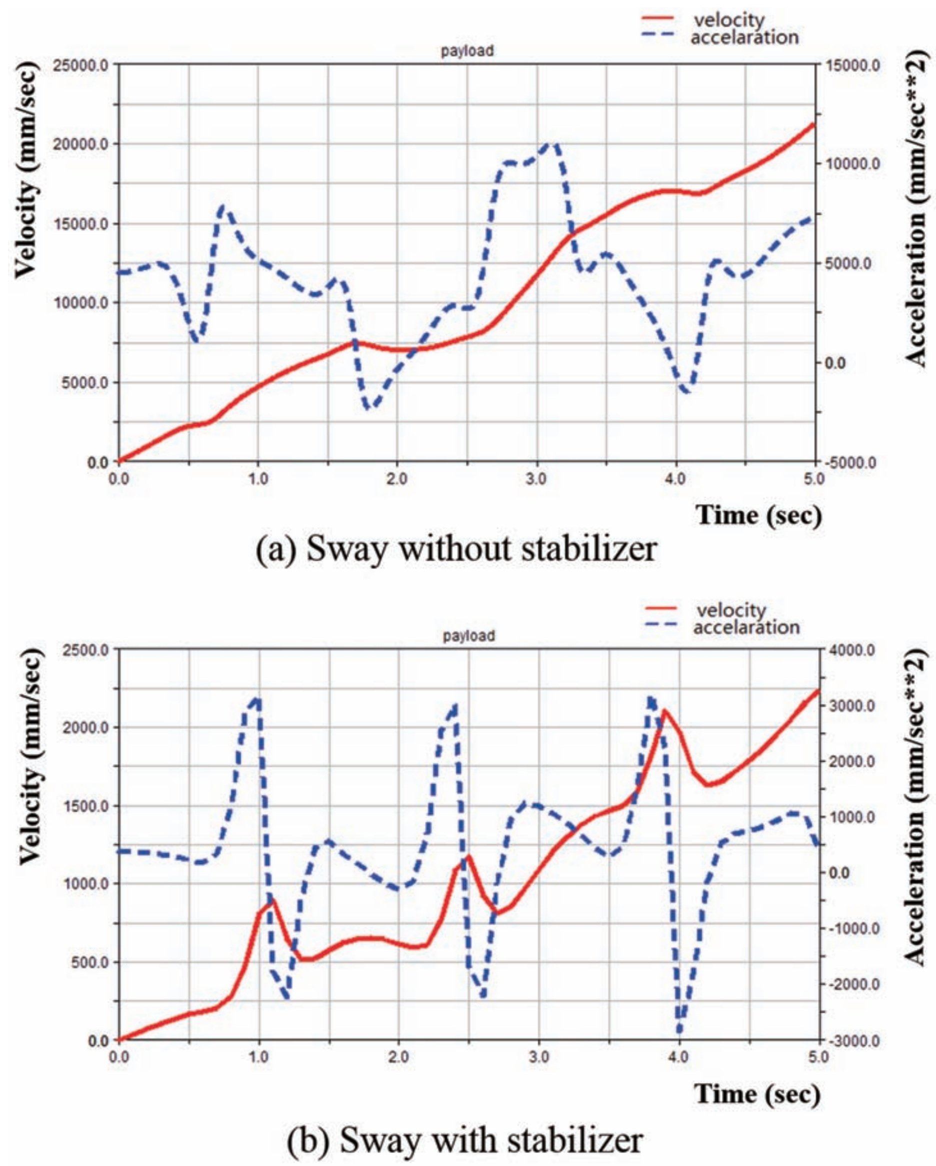


**Figure 5:** Comparison between hoisting system with/without stabilizer under environmental wind

Figure 5 shows the recorded sway intensity in the experiment. It can be observed that the development of velocity caused by the environmental wind is mitigated by the stabilizer. However, since the gyroscope only adjusts the attitude of hoisting system, the hoisting system is still subject to high velocity and oscillations caused by lateral forces. Therefore, the stabilizing system needs to enable the displacement control. In the second prototype, air ejectors are installed on the stabilizer to cancel out the displacement. The ejection frequency and amount of compressed air are calculated based on the information collected from electronic gyroscope and accelerometers. The final stabilizer (prototype 2) is illustrated in Figure 6.

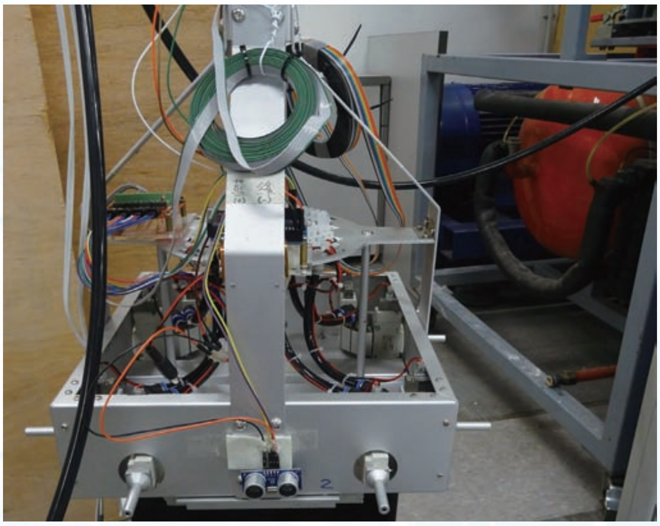

**Figure 6:** Final design of the stabilizer (Prototype 2)

## LIMITATION AND RECOMMENDATIONS

Although the developed prototype can effective stabilize the test load under simulated wind, the current design still subjects to several limitations. First, the simulated environment wind cannot accurately reflect the actual wind on site, since the natural wind shows strong dynamic randomness in term of both direction and speed. Therefore, it is suggested to test the performance of stabilizer in real construction sites. Second, the structural strength of stabilizer need to be future examined. Given the stabilizer is designed to link the cantilever hoist system and load, the stabilizer should has sufficient strength in case of unexpected structural failure.

Therefore, we suggest the following recommendations to realize the on-site implementation: firstly, investigating the stability of tower crane at higher height, especially for the skyscraper construction; secondly, future optimizing the installing locations of air ejectors to save space and energy; thirdly, refining the power supply and making the system compatible with compressed air tanks.

## CONCLUSION

Operations of tower cranes and gondolas under chaotic environment wind are extremely difficult. In this research, typical tower crane system is treated as a combination of double and inverse pendulum, which allows the oscillation of hoisting system under wind to be modeled and simulated. Combining both electrical and mechanical gyroscopes, a prototype stabilizer was designed. The performance of stabilizer's control mechanism is tested in the simulation model and a wind tunnel experiment. Both validation tests suggest the hybrid system is able to effectively reduce the sway intensity. However, due to the displacement caused by oscillation, it still takes substantial time for hoisting system stop swaying. Therefore, the final design (prototype 2) of the stabilizer integrates both gyroscopic elements and compressed air ejectors to balance torque and lateral force so that the payload can be stabilized. The developed hoisting system stabilizer can potentially improve the site safety and construction efficiency.

## ACKNOWLEDGEMENT

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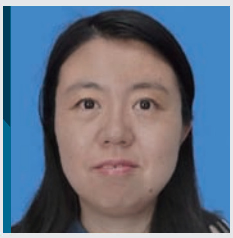

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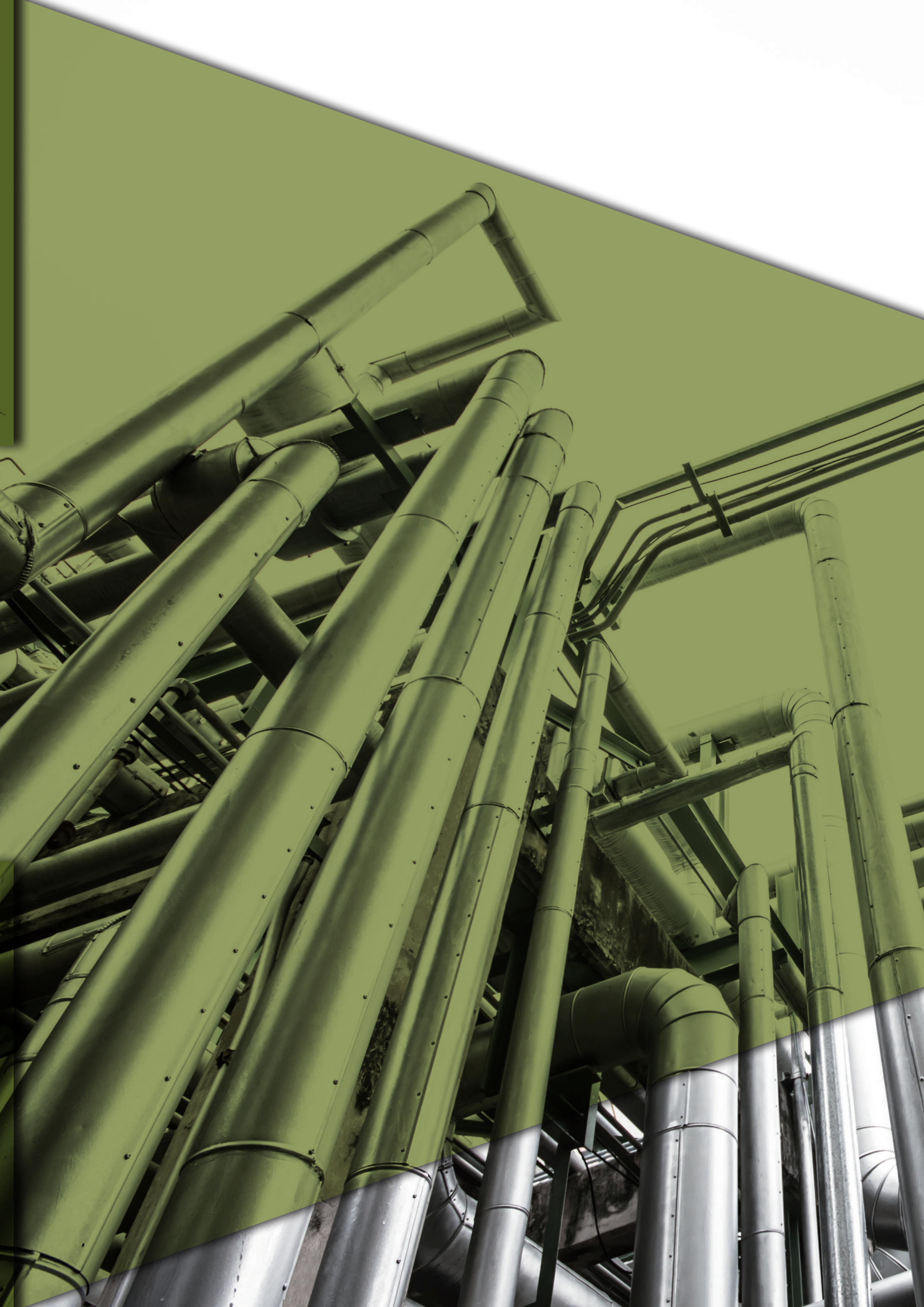

# Improving Electrical and Mechanical Safety in Construction

# IMPROVING ELECTRICAL AND MECHANICAL SAFETY IN CONSTRUCTION


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## ABSTRACT

Electrical and mechanical (E&M) installations are significant to most construction projects regardless of new construction works or repair, maintenance, alteration and addition (RMAA) works. E&M works consist of various specialist trades, including fire services installation, electrical wiring, plumbing and drainage, air-conditioning installation, and lift and escalator installation. To formulate effective strategies to prevent E&M related accidents in construction, a full investigation into the major causes of accidents and corresponding improvement measures is extremely important. The aim of this research is to provide a thorough E&M safety investigation in the construction industry. A combination of the results of focus group meetings, interviews, case studies and questionnaire survey, major causes of E&M accidents in new construction works and RMAA works are identified. Based on the research findings, recommendations on improving safety of E&M works are promulgated, and these include: solicit support from developers and main contractors, set up a reasonable project schedule, attract new entrants, develop and implement safety procedures and risk assessment process, extend Pay for Safety Scheme (PFSS) to frontline workers and specific safety measures for electrical works and working at height. Besides, to design for safety for E&M maintenance works and new technologies are proposed to reduce the risk of E&M works.



**Keywords:** Electrical and Mechanical; Safety; New construction works; Repair and maintenance works; Hong Kong.


## 1. INTRODUCTION

E&M works involve a wide range of building services trades such as air-conditioning, fire services, plumbing and drainage, electrical wiring and lift installation and maintenance works. E&M safety is a vital issue in promoting construction safety. Understanding the underlying relationship between E&M works related injuries and factors leading to the injuries are important to enhance the E&M works safety. Deterioration of fire services system, water pipes and electrical wiring usually occurs in old buildings which lack of proper maintenance. To uphold the ageing building stock properly and enhance public safety in a sustainable way, the Hong Kong SAR government has initiated the Mandatory Building Inspection Scheme (MBIS) in 2012 to stipulate the legal requirements for owners to inspect and repair their ageing buildings on a regular basis. Around 2,000 target buildings will be selected by the government for inspection each year and the owners should carry out corresponding repair and maintenance works each year. The scope of inspection is not only limited to the structural elements of buildings, but also the fire safety elements and drainage system. Besides, with an increasing housing demand, it is expected that the volume of E&M works will continue to increase.

With an expanding volume of E&M works, it is foreseeable that the number of E&M accidents will also increase. The Hong Kong Federation of Electrical and Mechanical Contractors Limited (HKFEMC), the biggest trade association of E&M works, has long identified E&M safety a key issue to address. HKFEMC has expressed serious concerns for safety of their member practitioners in different occasions. E&M installations and maintenance represent a significant proportion of practitioners working in the construction industry. E&M works practitioners are always exposed to the hazards of working at height, with electricity and machinery. It is important to have a better understanding about the causes of E&M works related accidents. This research project aims to reveal causes of accidents of E&M works and provide recommendations to improve safety and health of E&M practitioners. There are four specific objectives with this research, including (1) to understand the general practice and procedures in E&M installation; (2) to determine the causes of E&M accidents; (3) to identify effective measures to be implemented in order to reduce E&M accidents on construction sites; and (4) to give recommendations to various stakeholders to enhance E&M installation safety. A comprehensive research approach is adopted to formulate holistic and practical measures to identify the root causes of accidents and their relative degrees of importance; and prevent accidents related to E&M works.

## 2. ELECTRICAL AND MECHANICAL SAFETY ACCIDENT STATISTICS

As official statistics on E&M works related accidents are not available in the public domain, a systematic search for E&M fatal cases was conducted through "Wisenews", which is an electronic database of newspapers, magazines and journals. Most of the major local newspapers such as Apple Daily, Hong Kong Commercial Daily, Hong Kong Daily News, Ming Pao, Oriental Daily News, Sing Tao Daily, the Sun and Wen Wei Po, etc are included in the archive. This research reviews E&M fatal accidents that occurred in the Hong Kong construction industry reported in local newspapers from 1 January 1998 to 31 December 2014. Those articles which mentioned these keywords but did not have a complete coverage of E&M fatal accident were discarded. Sixty relevant accidents were recorded and found in WiseNews. Details of these cases were cross-referenced and verified by at least two reports of different newspapers before entering the corresponding details to the EXCEL template for further analysis.

The results showed that there were at least 60 E&M works related fatal cases between 1998 and 2014 in Hong Kong. Approximately two-thirds of the 60 fatal cases were related to RMAA works. There were 39 E&M works related accident cases occurred in RMAA works which far outweighed that of new construction works (n=21). The number of E&M accidents occurred in July and October was higher than other months especially from December to April (Figure 1). The high temperature and humidity environment with low wind speed is insufferable and unfavorable to safety and health of construction workers (Yi and Chan, 2014). It is believed that prolonged work in a hot environment may result in fatigue, heat-related illness and a higher chance of injury (Wong *et al.*, 2014; Rowlinson and Jia, 2015). Fatalities due to fall of person from height and contact with electricity accounted for over 75% of all occupational fatalities in the electrical and mechanical industry (Figure 2). Among various E&M trades, air-conditioning installation was the most common trades leading to fatality. This trade accounted for a total of 33% of all E&M works related fatal cases (Figure 3). This may be due to the fact that air-conditioning works extensively involve working at height outside the external wall. This greatly increases the likelihood of fall accidents. Furthermore, the 60 E&M works related fatal accidents have been analysed by E&M trades and type of works. The results show that risks of air-conditioning repair and maintenance works is the highest. The number of fatal cases related to RMAA of air-conditioning works (n=17) is far beyond the new air-conditioning works (n=3) (Figure 4). It may be probably due to the fact that the repair works of air-conditioning are often involved in working at height outside the external wall of a building. RMAA works generally last for a short construction period with less resources such as safety equipment and supervision. The number of fatal accidents of lift works is second only to that of air-conditioning works. Some lift systems of buildings are designed without consideration of repair and maintenance works. There is no entrance at the bottom of the lift pit. The workers are in danger when they access the lift pit. Fall accidents may easily happen. Besides, lift workers often work inside the lift shaft, on the lift car top or in the machine room, the working condition is unfavorable to workers.

Among different types of accidents, fall of person from height and electrocution are regarded as the top two killers of E&M works (Figure 5). Nearly 50% and 30% of the fatal cases are related to falls of person and electrocution respectively. Therefore, special attention should be paid to the E&M works which involve working at height and electricity. All safety procedures and associated personal protective equipment should be strictly followed.

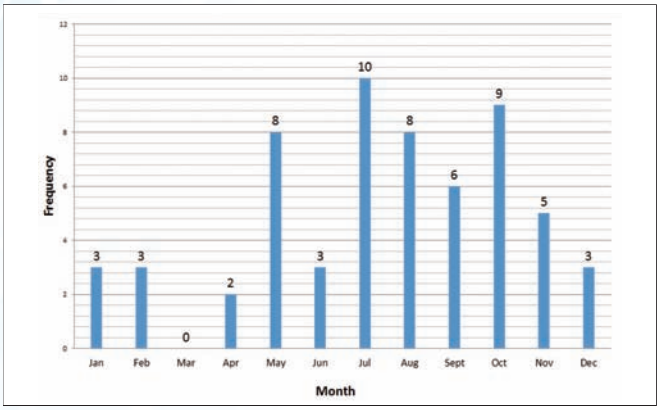


**Figure 1:** Number of E&M works related fatal accidents from 1998 to 2014 - analysed by Month

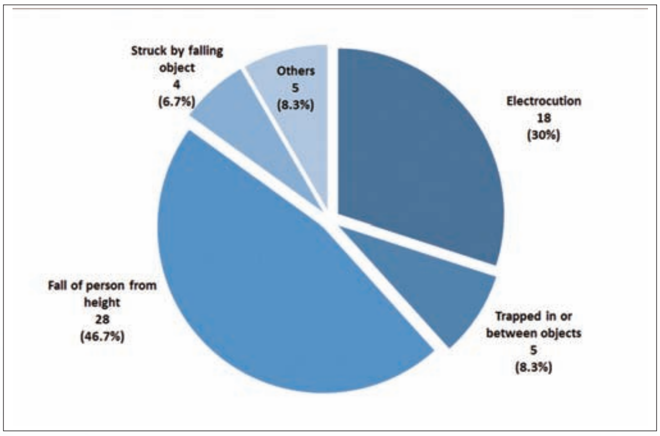


**Figure 2:** E&M works related fatal accidents from 1998 to 2014 – analysed by type of works and type of accidents

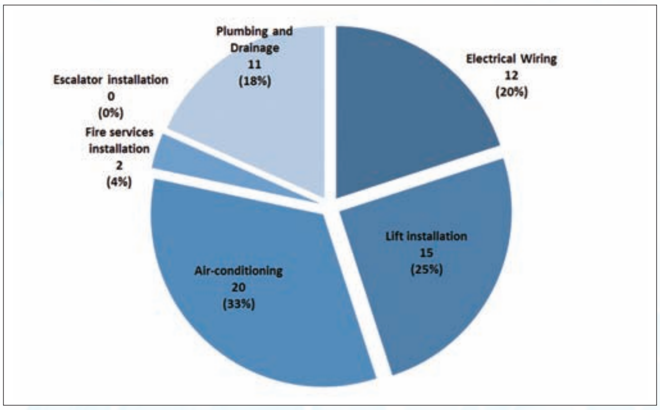


**Figure 3:** Number of E&M works related fatal accidents from 1998 to 2014 - analysed by trade of works

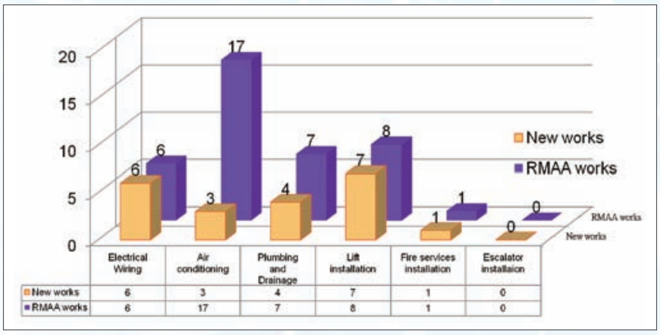


**Figure 4:** E&M works related fatal accidents from 1998 to 2014 – analysed by trades and type of works

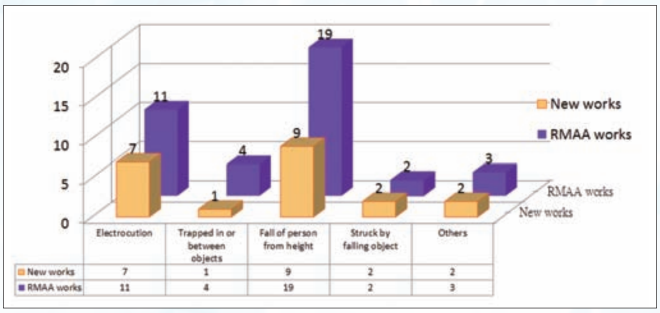


**Figure 5:** E&M works related fatal accidents from 1998 to 2014 – analysed by type of works and type of accidents

## 3. RESEARCH METHODS

A combination of qualitative and quantitative methods is adopted in this research to derive the respective benefits of using both approaches. The research began by launching an extensive review of safety research on E&M works from textbooks, professional journals, conference proceedings, refereed publications, research monographs, workshop seminars, and internet materials across different countries. The review is essential to identify the factors leading to accidents of E&M works and facilitate the data collection process. The data collection process comprises four key stages: (1) focus group meetings; (2) case studies; (3) structured interviews; and (4) a questionnaire survey.

### 3.1 Focus Group Meetings

Two focus group meetings were conducted with (1) trade unions' representatives and frontline tradesmen; and (2) representatives from the HKFEMC. A total of 19 E&M practitioners participated in the two focus group meetings. The focus group meeting participants were invited through related E&M trade unions and associations. The participants were invited to provide their expert knowledge on safety issues of E&M works, the root causes of E&M accidents and preventive strategies and measures. Focus group meetings provided a general picture of the safety problems of E&M works and also helped in developing templates for structured interviews and a questionnaire survey.

### 3.2 Case Studies

An accident database entitled "Public Works Programme Construction Site Safety & Environmental Statistics" (PCSES) system is established and maintained by the Development Bureau for recording the accident statistics of public works contracts. A total of 421 sets of accident cases related to E&M works for the period between 2001 and 2015 were provided by the Electrical and Mechanical Services Department (EMSD) and the Architectural Services Department (ArchSD) of the Hong Kong Government from the PCSES system for analysis. Based on the injury report form, an EXCEL file with 18 variables describing the characteristics of the accident was developed for data input and analysis.

Besides, with the consent of the Coroner's Court, the case files of E&M works related fatalities between January 2010 and July 2013 were collected for in-depth analysis. Excluding cases which are being processed, there were 13 case files that were related to E&M works in this period. A rich set of information including autopsy report, toxicology report, medical report, investigation report and death investigation report was obtained from the coroner's death investigation case file. More importantly, a series of recommendation has been suggested by the Coroner's Court, the Labour Department and relevant government departments to prevent the reoccurrence of similar fatalities. The advantages of referring to the coroner's reports are that the data is highly reliable and strictly validated by police investigation of the circumstances and causes of the accidents (Gephart, 1993 and Goh *et al*., 2012).

### 3. 3 Structured Interviews

Ten structured interviews were conducted with key trades of E&M installations, including air-conditioning, fire services, plumbing, and electrical works. Interviewees include representatives from the government, quasi-government organizations, professional institutes, contractors' associations, and trade unions. Interview questions were compiled based on the literature review and also the results of the focus group meetings. The interview questions were designed to identify the causes leading to common E&M accidents and strategies for improving safety of E&M work practitioners.

### 3.4 Questionnaire Survey

A questionnaire survey was designed based on literature and findings from the case studies and structured interviews. Respondents were requested to prioritize the causes of E&M accidents and importance of recommendations for enhancing E&M works safety. Two sets of questionnaires were developed for management staff and frontline staff respectively. Questionnaires were dispatched via industry forum and presentations. 371 completed questionnaires were collected. The advantages of conducting questionnaire survey in this way are that respondents can get immediate assistance from investigators of the proposed studies and thus improving quality of their responses. Also, respondents attending the industry forum have interests in E&M safety. They are more likely to give reliable and informed responses based on their working experience and expertise.

## 4. RESEARCH FINDINGS

Based on the combined findings from the focus group meeting, interviews, case studies and questionnaire survey, the key research results are reported and discussed in this section.

### 4.1 Major Categories of E&M Works Related Accidents

Based on the research results, major categories of E&M accidents were summarized in Table 1. It is revealed that the major types of accidents related to E&M works are fall of person from height and electrocution. Fall of person from height is regarded as the major type of accidents related to air-conditioning works in both new construction works and RMAA works. Air-conditioning works comprise of work at height outside the external wall and use of ladder inside the building. Use of ladder is very frequent in new air-conditioning works and maintenance works. Trapped in or between objects and injured by moving machinery, striking against fixed or stationary object and struck by falling object would be commonly occurred in lift installation and maintenance works. The major types of accidents related to fire services installation works are fall of person from height, injured whilst lifting or carrying, contact with moving machinery and hazardous energy. As most of the plumbing works are mainly located at height, working platform cannot be used due to the limited size of working area. Only ladder can be used to carry workers for works at height, fall accidents may easily happen. When replacing drainage pipes and carrying other plumbing works, workers may be cut by the sharp edge of a pipe or be injured by using a hand tool. A worker may be injured by fragments when welding and cutting pipes without suitable protective measures. Struck-by accidents may happen when the pipes are not fixed or anchored properly when lifting or unloading. Demolition of pipe and drainage works would be dangerous for workers. Sludge in pipe may contain hazardous gases which may cause suffocation. The major type of accidents related to electric wiring works include fall of person from height, contact with electricity or electric discharge and injured whilst lifting or carrying. Electrocution is a major type of E&M related accident. For electrical wiring works, the E&M workers are vulnerable to electric shock hazard whilst working on the conductive parts of the electrical cable which has not been properly isolated from the power source.

**Table 1:** Major categories of accidents

| Major categories of accidents | Air-conditioning | Lift/ escalator | Fire services | Plumbing & drainage | Electrical Wiring |
|---|---|---|---|---|---|
| Fall of person from height (e.g. ladder, working platform) | ✓ | ✓ | ✓ | ✓ | ✓ |
| Electrocution | ✓ | ✓ | | | ✓ |
| Cut during the working process | | | | ✓ | |
| Slip and fall on same level | | ✓ | | | |
| Trapped or injured by moving machines | | ✓ | ✓ | | |
| Injured whilst lifting or carrying | | | ✓ | | ✓ |
| Struck by falling object | | ✓ | | ✓ | |
| Laceration by sharp edges or tools | | | | ✓ | |
| Suffocation in confined space | | | | ✓ | |
| Striking against fixed or stationary object | | ✓ | | | |
| Contact with hazardous energy | | | ✓ | | |

Some interviewees also indicated that the accident rate of RMAA works is substantially higher than new construction works. The major types of accidents related to E&M RMAA works are fall of person from height (i.e. from ladder or working platform), electrocution and cut during the working process. Although the type of accidents of RMAA works is limited, the occurrence is frequent. It may be explained by the fact that the working condition of new construction works is comparatively better than RMAA works. The construction processes of new works are relatively well-planned whereas those of RMAA works are rather unforeseeable (Hon and Chan, 2013). RMAA works generally last for a short construction period with fewer resources such as safety equipment and supervision.

## 4.2 Major Causes of E&M Accidents

E&M works are regarded as a high risk specialist trade in construction. Based on the results of focus group meetings, case studies, structured interviews and questionnaire survey, the major causes of E&M accidents in new construction works are summarized.

### 4.2.1 Compressed Working Schedule

The results of the focus group meetings, interviews and questionnaire survey indicated that compressed working schedule was regarded as the most significant causes of E&M accidents in new construction works. As the installation of E&M works needs to follow the general builder's works, it makes E&M installation works always be put in a passive position at the last construction stage. The delay of previous construction works would carry on to the E&M works. Even though E&M works are postponed due to delay of completion of the general builder's works, E&M contractors still need to strictly follow the master programme and usually no extra time provision is allowed. An unreasonable project schedule may bring about safety problems, adversely affect the safety performance of E&M works and prone to accidents.

### 4.2.2 Long Working Hours

"Long working hours of E&M workers" was regarded as one of the major causes of E&M accidents in the results of focus group meeting and interviews. It was also ranked as the second top major causes of E&M related accidents in construction by the questionnaire respondents. The interviewees pointed out that the execution of safety procedures for the workers may be deviated due to the pressure of rush working schedule, heavy workload and long working hours. Tight project schedule involving long working hours may result in fatigue of workers and reduce their concentration and increase errors in judgment.

### 4.2.3 Complex Working Environment

As construction is always risky due to its complexity and continuously changing working environment as well as the associated hazardous characteristics of E&M works, E&M workers who are less familiar with the site and working environment are more prone to accidents. The site condition of new construction works is generally untidy with inadequate working space. Sometimes, the working area is occupied by construction materials. With limited working area, the E&M workers can only use "A" ladder instead of working platform for their work. It highly increased the risk of working at height. Moreover, multi building service trades are often concurrently working in the same location (Tommelein and Ballard, 1997). Working under a crowded and messy working environment, workers may be prone to accidents. The housekeeping or orderliness also influences workers' exposure to slip, trip or fall hazards. Carrying out E&M works on slippery or uneven floor may cause slip, trip or fall accidents when workers are not fully concentrated on their works.

#### 4.2.4 Manpower Shortage

The questionnaire survey respondents are divided into two groups for comparison (i.e. management staff and frontline/ site staff) who are two primary parties involved in E&M works. Significant differences in the ranking between respondent groups were found in this item "Manpower shortage". The frontline/ site staff ranked this item as the third major causes of E&M accidents whereas the management staff ranked it as the tenth. This result indicated that the frontline staff considered manpower shortage for E&M works as a serious problem whiles the management staff do not treat this as a critical issue. With the rolling out of major infrastructure projects and considerable housing development projects, the construction industry faces the pressure of manpower shortage. As most of the E&M workers are skilled workers with special training, the manpower shortage problem is particularly serious in E&M industry. The manpower shortage issues challenges to the work progress as well as the workers' safety.

#### 4.2.5 Lack of Risk Assessment and Safety Plan

E&M installation works are regarded as high-risk operations in construction process. Due to the tight working schedule of E&M works in new construction works, the process of risk assessment may be neglected, which may lead to accidents. It is important to carry out appropriate risk assessment by a competent person to ensure safety and health of workers. An appropriate risk assessment may include an effective safety plan with appropriate safety procedures and measures.

## 4.3 Recommendations

In order to improve the safety performance of E&M works in new construction works, some implementation strategies are suggested as follows.

#### 4.3.1 Support from Developers and Main Contractors

The participants of interviews and focus group meetings strongly suggested that the support from developers and main contractors would effectively enhance the safety performance of E&M works. Support from the clients and the main contractors to drive the safety culture and safety attitudes of workers that can fundamentally improve the safety of E&M works.

Corporate culture, allocation of safety resources and support of top management have significant impact on project safety (Biggs, *et al*. 2013 and Fang and Wu, 2013). The safety culture of a company will effectively enhance the safety awareness of workers. It is recommended that safety campaign should be arranged regularly by main contractors to encourage safety awareness of their subcontractors. The reward criteria may be base on safety performance of the subcontractors (i.e. proper use of ladder and good housekeeping, etc.), coupons for safety equipment will be awarded to well-performed subcontractors. It is important to educate frontline workers on construction safety. This would require the support and promotion of a company's top management.

#### 4.3.2 Reasonable Project Schedule

A reasonable project schedule is important to improve safety performance of E&M works. With a tight working schedule and long working hours, workers may neglect the safety procedures and overlook the risks of working environments (Mohamed, 2002; Tam and Fung, 2011 and Chan and Choi, 2015). Consideration of safety issues when developing the project schedule at the planning stage would substantially reduce the risk of accidents during construction. The formulation of reasonable project schedule in E&M works needs fully support from developers. It is recommended that through the enhancement of the current common standard forms of contract, compulsory comments from E&M nominated subcontractors should be included as part of the essential substantiations of master programme and deliver recover measure submissions from main contractors to contract supervisors. In addition, the timing of comments and decisions from contract supervisors on main contractors' extension of time claims should be well defined in contract conditions, in order to avoid the situation of self-accelerations and unnecessary progress compression in E&M works.

### 4.3.3 Attract New Entrants

The problem of manpower shortage in E&M industry has become more serious as the young generation is unwilling to work on construction sites. It is suggested that the government should take the initiatives to attract young people to join the industry. Some recommended measures include improving the image of the industry, enhancing the site facilities, and increasing the income and welfare of E&M workers.

### 4.3.4 Develop and Implement Safety Procedures and Risk Assessment Process

Some interviewees expressed that it is important to conduct risk assessment by safety personnel at the tender stage. This helps to identify hazardous works such as confined working spaces, working at height and corresponding safety equipment, and to estimate the cost for safety investment (e.g. provision of working platform and scissor lift). It is also required to make a risk assessment of health and safety to employees and others who are exposed to construction sites, especially for specific hazards (e.g. working at height, hazardous substance, manual handing, and using of plant, etc.). A risk assessment may identify people who are being affected by the activity and the requirements of personal protective equipment then provide suggestion on the additional risk control measures and applicable guidance related to the operation. Besides, good safety planning and coordination, sufficient work spaces and time, good sequence of work, provision of fall prevention devices can effectively reduce the risk of E&M works.

### 4.3.5 Extend the Pay for Safety Scheme (PFSS) to Frontline Workers

The research of Wong and So (2004) and Ng (2007) indicated that PFSS is an effective tool to improve construction safety by encouraging contractors to perform safely on-site. Under the Pay for Safety Scheme (PFSS), when main contractors have complied with the stipulated safety requirements, payment will be made to the contractors. However, no incentive is awarded to the frontline workers for carrying out those safety items. Some previous studies indicated that subcontractors and their workers have a less positive attitude towards safety than their main contractor counterparts (OSHC, 2003; Chan *et al.*, 2005). It is suggested that PFSS should be extended to subcontractors and frontline workers. The main contractor may apportion part of the payment received from the client under the PFSS to their E&M trade subcontractors. For instance, the main contractor would pay or award their subcontractors for fulfilment of stipulated safety requirements. The subcontractors may award their workers (e.g. cash or coupons) based on their safety performance for enhancing their motivation. It is suggested by the interviewees that the government should actively promote construction safety through implementation of incentive schemes.

### 4.3.6 Application of New Technologies

***Push-fit Pipe***

Push-fit pipe is a new technology in pipe design. The use of push-fit pipe may facilitate a safer working process of plumbing works. The push-fit pipes can be jointed and fixed without welding process. It can reduce accidents related to cut by hand tool or burn when welding.

***Building Information Modelling (BIM)***

BIM can be applied for hazard identification and correction during planning and construction stages. It is an advanced method for creating a virtual representation. With the 3D visualization, construction project teams know exactly the operation procedures and safety hazards. Hence, the frontline site management can set up corresponding preventive measures for workers. It would be valuable to establish a systematic database of 3D simulated method statement for E&M installation works. Some supporting documents such as safety precautions, standard working procedures and stipulated training certificate for E&M workers may also be illustrated in each 3D simulated method statement.

With the publication and implementation of BIM Standards from the Construction Industry Council (CIC) in September 2015, more BIM applications in construction lifecycle are viable. 3D simulations can be used on briefing or training notes to demonstrate the working procedures and safety plan directly to the workers. The feasibility of using Cloud-based BIM platform for workers should be explored. The workers can download BIM video directly via their mobile phone application. BIM creates virtual model which can be applied for coordination with different E&M trades. It would be useful for detecting and reporting of clashes and design conflicts and space analysis for large equipment (e.g. generator for electrical works), with reference to the construction sequence.

***Guided Suspended Working Platform (Guided-SWP)***

Conventionally, lift installation works require scaffolding in the lift shaft. It is suggested that a guided suspended working platform should be used instead of bamboo scaffolding inside a lift shaft to provide a comfortable and safe working environment for lift installation workers. By using Guided-SWP, lift installation workers can move along the lift shaft to install the lift equipment such as guide rails and landing door operators, etc. in a safer and more efficient manner. It can also reduce the risk of lift shaft works.

***Use of Rechargeable and Wireless Hand Held Tools***

The current trend of the construction industry is using wireless hand held tools such as electrical drill, saw, cutting machine and handy task lights which is battery operated and rechargeable to replace traditional tools. The advantages of using wireless hand tools include (1) prevent accidents related to contact with electricity or electric discharge; and (2) prevent trip over electrical wire.

### 4.3.7 Enhance Training and Supervision

It would be most effective to formulate targeted safety measures for those high risk groups. It is recommended that workers who are new to a construction site should receive more training and be mentored by experienced E&M specialist. Suitable training should be provided to workers before they start working, before being assigned to a job which requires new skill, and after any deficiency is detected (Ling *et al*. 2009). Lee (1991) promoted the introduction of safety orientation programmes for new workers to strengthen their safety awareness. With adequate safety training, the competent safety person would be responsible to identify safety hazards, check safety equipment, and remind the corresponding workers constantly. The safety personnel should closely supervise the workers involved in high-risk activities such as electrical wiring works and work at height etc., to ensure proper use of personal protective equipment and correct any unsafe action and condition.

### 4.3.8 Safety Measures for Electrical Works

Electrical hazards are significant issues that threaten the safety of E&M workers. Special attention should be given to works involving electricity. The use of "Lock out tag out device" is recommended for electrical works. It is an effective safety procedure which is used in the construction industry to ensure that no hazardous power sources will be turned on accidentally when the E&M work is carry out. Generally, the key for the lock out device would be kept by the person in charge for the electrical works. The "Permit-to-Work" system should be conducted by Registered Electrical Worker (REW) and the Safety Officer (required in ArchSD's projects) to assess and ensure that the risk at work is properly be controlled. The "Permit-to-work system" should include (1) risk assessment of the task; (2) identify the hazards; (3) define safety precautions; (4) implement the system; and (5) monitor the system. For preventing electrocution accidents in ArchSD's projects, it is a contractual requirement that all portable electric tools, site lighting and other electrical devices should be operated at 110 volts obtained by the use of a step-down transformer.

### 4.3.9 Safety Measures for Working at Height

A vast majority of accidents are caused by fall of person from height and results in severe injuries. It is suggested that safety measures should be implemented to prevent the recurrence of fall accidents. E&M works often involve the use of ladders. Ladder was found to be the most common agent involved in fall accidents. Workers were injured with ladders being used to perform installation tasks or gain access to areas in most accident cases. Ladder is designed only for temporary use or providing access to different elevations. Workers should be prevented to perform prolonged tasks on ladders (Bentley *et al*., 2006). It also indicated that "better control" and "enhance monitoring" of using ladders are the key measures to ensure the safe use of ladder, thus, minimizing fall accidents from ladders. Safety checking system for equipment (i.e. ladders, hand tools, and safety harness, etc.) should be established to ensure all the equipment are in safe working order. Safe means of support such as platform ladder and working platform should be provided for accessing or working at height to reduce accidents related to work at height. It is encouraged to use platform ladder instead of "A" ladder for E&M works. It provides a more stable platform with railing for workers and reduces accidents related to work at height. When the task involves electrical works, fibre glass ladder should be used. It is recommended to enhance promotion of platform ladder within the construction industry. As the resources of small and medium enterprises (SMEs) are inadequate, it is valuable to explore the feasibility to provide financial support for SMEs to purchase platform ladder.

## 5. CONCLUSION

This project investigated the causes of accidents of E&M works and provided recommendations to improve safety and health of E&M practitioners. The research would be vital for the industry practitioners and relevant Government

Departments to enhance the safety performance of E&M works. This research project provided an overview of E&M works related accidents in Hong Kong, identifies the underlying causes of accidents and provides practical recommendations through a series of research tools including focus group meetings, cases studies, structured interviews and questionnaire survey. E&M works related accidents collected from the ArchSD, the EMSD and the Coroner's Court. Two focus group meetings and ten face-to-face interviews were conducted to identify safety issues for E&M works, the root causes of E&M accidents and preventive strategies. Questionnaire survey was conducted to prioritize the causes of E&M accidents and the possible recommendations. The results of the research generated valuable insights on improving the safety performance of E&M works. Recommendations to avoid recurrence of similar E&M accidents also were provided. The research outcomes would be useful for safety managers and project managers to estimate the associate risks of E&M accident occurrence, facilitate the allocation of safety resources to prevent E&M works related accidents and achieve a safer working environment. Although the analysis of E&M work related accidents were studied based on Hong Kong, the research findings are believed to be applicable to other countries as well.

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## *BIOGRAPHYS*

Professor Francis K. W. WONG obtained his BSc (Hons) in Building Degree from the Brighton Polytechnic in the U.K. He worked for a building contractor in Hong Kong in 1980 and the Mass Transit Railway Corporation two years after. In 1984, he joined the Department of Building and Real Estate of the Hong Kong Polytechnic University. He completed his PhD Degree at the South Bank University in England in 2000. In terms of community and professional services, he was the Chairman of the Safety Specialist Group of the Hong Kong Institution of Engineers (HKIE) in Year 1999/2000, and Vice-chairman of the Construction Safety and Health Committee of the Occupational Safety and Health Council in Hong Kong from 2001 to 2004. Prof. WONG is currently the chairman of the Health and Safety Advisory Sub-Group (Hong Kong and South China) of the Chartered Institute of Building (CIOB) and a Member of the Construction Site Safety Committee of the Construction Industry Council (CIC).

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# Wearable IMU-Based Real-Time Motion Warning System for Work-Related Musculoskeletal Disorders Prevention in Construction

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# WEARABLE IMU-BASED REAL-TIME MOTION WARNING SYSTEM FOR WORK-RELATED MUSCULOSKELETAL DISORDERS PREVENTION IN CONSTRUCTION

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**ABSTRACT**

With a high prevalence amongst construction workers, work-related musculoskeletal disorders (WMSDs) around lower back and neck are precursors of operational injury in the construction industry. As significant risk factors of WMSDs, insecure operational postures and holding time should be proactively prevented to protect workers from ergonomic hazards and injuries, meanwhile improving project performance. The study develops a sensor-based real-time motion warning personal protective equipment (PPE) for WMSDs prevention based on wearable inertial measurement units (WIMUs), considering operational convenience for practical utility. A data processing algorithm and a real-time motion warning algorithm are proposed that are capable of automatically assessing and warning ergonomically hazardous postures with alarms through a connected smartphone application as soon as dangerous operational postures leading to lower back and neck pain are detected. The system was tested and validated with robust clinical motion data output and effective alarm ringing in a laboratory test and a field experiment on a construction site in Hong Kong. The proposed PPE provides an alternative to help construction workers prevent WMSDs without disturbance and distraction in operations.

**Keywords:** WMSD prevention, WIMU, Motion warning, PPE, Alarm.







## 1. INTRODUCTION

Notwithstanding technological advances, on-site construction continues to be a labor-intensive and heavy manual industry (Jarkas, 2015; Eaves *et al.*, 2016). The physical condition and health status of laborers remain to be a significant determinant of project performance (Sadosky *et al.*, 2015). However, a large percentage of work-related injuries remains to be a major concern and work-related musculoskeletal disorders (WMSDs) are amongst the most frequently reported causes of lost and restrictions in the construction industry (Choi and Borchardt, 2016), with general incidence rate of more than 30% according to the report of Bureau of Labor Statistics in the U.S. (BLS, 2014). A survey by Forde, *et al.* (2005) found WMSDs to be especially severe for rebar ironworkers that are predominantly concerned placing and tying reinforcing bars in in-situ concrete work. In particular, the prevalence of self-reported lower back pain was high as 56% amongst rebar ironworkers in this survey. Many manual operations on construction site like rebar ironwork require workers to maintain non-neutral trunk postures such as stooping, squatting and kneeling for long working hours during workdays, which significantly increases the risk of lower back injuries (Forde and Buchholz, 2004; Umer *et al.*, 2016). Thus, it is of great importance to provide practical cost-effective solutions for on-site construction workers against postural hazards that significantly contribute to WMSDs.

Many studies in applied ergonomics in workplace have been conducted to assess postural hazards of WMSDs (Hignett and McAtamney, 2000; Buchholz *et al.*, 1996; McAtamney and Corlett, 1993). In the current situation, the development of inertial measurement units (IMUs) enables a precise measurement of postures and body movements for safety management in the construction industry (Chen *et al.*, 2014; Jebelli *et al.*, 2016a; Jebelli *et al.*, 2016b). Inertial sensor has been improved to be effective for the measurement of trunk inclination (Faber *et al.*, 2009). An activity tracking system based on IMUs for postural hazards assessment was also proposed for musculoskeletal disorders assessments (Valero *et al.*, 2016). However, on-site real-time alarms feature was not developed in previous research. As a result, ergonomic assessment or evaluation can only be provided to workers after their operations. In this way, ergonomic hazards may already cause negative consequences before the assessment. The workers cannot make timely adjustments to protect themselves from ergonomic risks, which is not sufficient for real-time WMSDs prevention on site. Real-time ergonomic assessment would be more effective for workers to understand what types of manual operations are ergonomically hazardous and how they can make adjustment and improvement to reduce the occurrence of ergonomic hazards. In addition, previous IMU-based interventions did not consider the holding time of dynamic postures for WMSDs prevention. Thus, contribution that can solve the aforementioned problems should be made for construction workers' WMSDs prevention in a real-time and practical way.

This paper has improved and validated the IMU sensor technology, turning it into wearable sensor-based real-time motion warning personal protective equipment (PPE) that is capable of automatically assessing ergonomically hazardous postures and warning the wearer with chosen alarms through a connected smartphone application as soon as ergonomically hazardous operational postures and holding time leading to lower back and neck pain are detected. Such dangerous behavior and holding time thresholds are preset into the WIMU-based system according to an ISO standard regarding the optimal static working posture to minimize the risk of developing MSDs in healthy adults (ISO 11226, 2000). The standard is a landmark in musculoskeletal disorders prevention and control (Delleman and Dul, 2007), specifying recommended limits and acceptable body kinestate in terms of body angles and time frame for operational postures. A smartphone application is attached for dangerous motion assessment and alarm delivery using received data. Construction workers will benefit from the self-awareness of risk postures that may lead to lower back and neck pain: they will be able to timely adjust head, neck or trunk postures to more acceptable manners (ISO 11226, 2000) in order to decrease WMSDs hazards in advance.

## 2. OVERALL DESIGN OF THE SYSTEM

This section illustrates the system framework and algorithm development in the WIMU-based system and the mechanism for preventing lower back and neck pains.

### 2.1 Framework of the WIMU-based real-time motion warning system

Figure 1 depicts the system framework and components of the WIMU-based real-time motion warning system. Two IMU sensors are mounted firmly on the back of a safety helmet and the middle-upper part of an operational reflecting vest with Velcro tape to avoid rotational noises caused by unstable adherence. It should be noted that when providing practical devices for on-site workers to prevent WMSDs using real-time data, a compromise between theoretical accuracy and practical utility is inevitable, due to the harsh conditions and environments around workers. Through careful balancing, two sensors are employed in the wearable system, which provide the acceptable reliability and accuracy based on the proposed data processing algorithms, while also giving consideration to operational convenience for practical utility in construction. Detailed algorithms are illustrated in the following sections. The locations of the two IMU sensors are also selected carefully according to the anatomical landmarks (Faber *et al*., 2009) because the location of the sensors could also influence the reliability of captured data (Joshua and Varghese, 2013). The arrangement of these IMU sensors in the wearable system is validated by practitioners to be convenient to use while conducting site activities.

Additionally, a smartphone application is integrated to receive and process data captured by the WIMU sensors via Bluetooth technology. The real-time sensor outputs are transferred to the attached smartphone application for data processing. Raw unit quaternion vectors generated by IMU sensors depicting the kinestate of body segments are translated into clinical parameters in term of flexion-extension, lateral bending and axial rotation of targeted body segment including head, neck, and trunk, with respect to calibrated reference coordinates (Goodvin *et al*., 2006) achieved by a real-time data processing algorithm.

Evaluation of clinical outputs would lead to 'Acceptable' or 'Not Recommended' judgements according to ISO 11226: 2000 (E), and these data would be compared with predefined hazardous angle thresholds of head, neck and trunk inclination. If the value of real-time operational angle becomes larger than the angle threshold of a treated part of the body, the application alarm system would be activated by the warning thresholds algorithm to send out tocsin sounds, warning workers that their current operational posture has a high risk leading to WMSDs if they do not make timely adjustments. If the value of the real-time postural angle is less than the predefined hazardous angle threshold yet still larger than acceptable threshold, the algorithm will start to estimate their accumulated holding time based on the linear relationship between static inclination angles of body segments and maximum holding time. Once the duration of a set of operational postures is larger than the corresponding accumulated maximum holding time, the alarm system would send out longer tocsin sounds, suggesting adjustments of current operational posture or an available pause for respite to avoid current postures.

All the motion data received and processed will be transferred to our safety management database to the backend server through site Wi-Fi. A large quantity of on-site practical operational motion data can be utilized to detect worker's operational habits and working patterns that may be different from relatively conservative ergonomic standards.

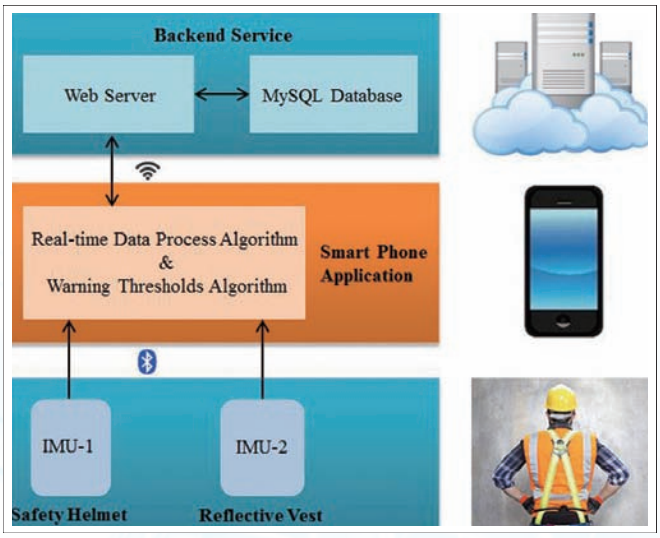



**Figure 1:** The WIMU-based real-time motion warning system framework.

## 2.2 Motion data collecting and processing

The locations of the two IMU sensors are defined based on the measuring procedure illustrated in a spinal motion measurement system for clinical practice (Goodvin *et al.*, 2006). The head and trunk are defined as two straight lines perpendicular to the plane of symmetry of the segment from the side view when a user looked straight ahead. The description and capture of the inclination illustrated in the standard are adjusted without losing reliability for convenient and practical purposes. As Figure 2 shows, the procedure begins with marking two points on both trunk and head segments denoted by T1-T2 and H1-H2, respectively. H1 and H2 are located closely to the lobe of the ear and the lateral corner of the eye respectively. Next, based on the aforementioned arrangements, the inclination angles of head and trunk are defined as the relative displacement angle of H1-H2 and T1-T2 respectively. The two IMU sensors are then located rigidly on the back of the safety helmet and the middle-upper part of the operational reflected vest. The movement of the upper sensor (IMU-1) approaches to the motion of the head that is deemed to a rigid segment. The movement of the lower sensor (IMU-2) approximately equals to the solid line T1-T2. The measurement of neck movement is represented by the relative position of head and trunk captured by the two IMUs with the approximate measured length of head and trunk:

$$V_{neck} = l_{head} \cdot v_{head} + l_{trunk} \cdot v_{trunk} \quad (1)$$

The normalized vector $N(V_{neck})$ can then be translated into the motion of the neck through the following algorithms.

Based on the aforementioned sensor arrangements, the real-time data captured by both IMU-1 and IMU-2 are comparable with the recommended references in the ergonomic standard, which are predefined in the smartphone application for ergonomically hazardous posture and holding time monitoring and alarming.

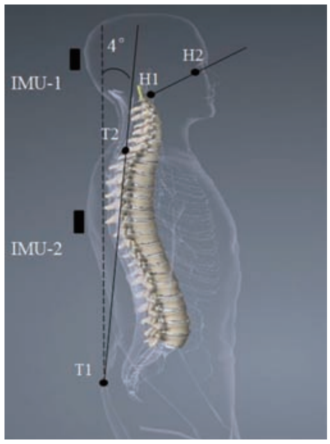



**Figure 2:** Determination of head and trunk inclination.

The tilt/twist method (Crawford *et al.*, 1999) is referred and adjusted for the algorithms in the system framework. The real-time motion parameters of the three body segments captured by the two IMU sensors can be transferred into the clinically intuitive format of flexion-extension, lateral bending and rotation (Goodvin *et al.*, 2006) through the postural data processing algorithm. Real-time angles of postures can be displayed on the attached smartphone screen for posture monitoring purpose. The output of each sensor is the following normalized quaternion,

$$q = [w, ai, bj, ck] \quad (2)$$

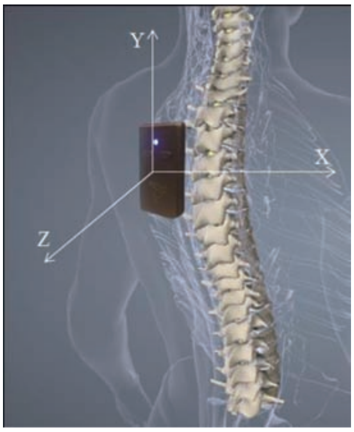
where $\|q\| = 1$. Taking IMU-2 as an example for illustration, the sensor's initial calibration state in default reference coordinates is shown in Figure 3. Two initial unit vectors are utilized to represent the calibrated state of the sensor for convenience. One is a positive unit vector in a quaternion format with w=0 along the Y-axis denoted $p_1$ to determine spine segment's tilt (ϕ) and tilt azimuth (θ) angles; the other is a negative unit vector in the same quaternion format along the Z-axis denoted $p_2$ to calculate twist (τ) angles, as shown in Figure 3. According to the multiplication formula of quaternions,

$$p' = qpq^{-1} \quad (3)$$

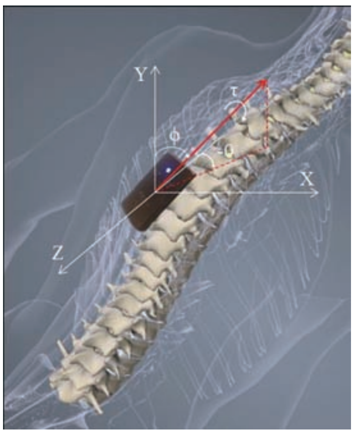
where $q^{-1}$ is the inverse vector of real-time quaternion $q$ generated by IMUs. Thus, the coordinates after rotation of both $p_1$ and $p_2$ in quaternion formats can be represented as:

$$\begin{aligned} p_1' = [0, &(-2w_1 \cdot z_1 + 2x_1 \cdot y_1)i, \\ &(w_1^2 - x_1^2 + y_1^2 - z_1^2)j, \\ &(2w_1 \cdot x_1 + 2y_1 \cdot z_1)k] \end{aligned} \quad (4)$$

$$\begin{aligned} p_2' = [0, &(-2w_2 \cdot y_2 - 2x_2 \cdot z_2)i, \\ &(2w_2 \cdot x_2 - 2y_2 \cdot z_2)j, \\ &(-w_2^2 + x_2^2 + y_2^2 - z_2^2)k] \end{aligned} \quad (5)$$




(a) Trunk IMU sensor calibration in the reference coordinate.




(b) Trunk inclination tilt (ϕ), tilt azimuth (θ) and twist (τ) angles.

**Figure 3:** Illustration of data collecting and processing.

Tilt angle can be determined by using the projection of unit vector $p_1'$ onto the Y-axis (see Figure 3) with the use of the following arccosine function:

$$\phi = \arccos\left(w_1^2 - x_1^2 + y_1^2 - z_1^2\right) \quad (6)$$

where, the denominator in the arc cosine formulation equals to 1 because of the unit vector. The measured ranges of tilt angle are 0-180° during flexion movements forward from the initial position and -180°-0 during extension backward from the initial position. The tilt azimuth angle can be determined by the projection of the same unit vector onto the X-Z plate using the arctangent function:

$$\theta = \arctan\left(\frac{2w_1 \cdot z_1 - 2x_1 \cdot y_1}{-2w_1 \cdot x_1 + 2y_1 \cdot z_1}\right) \quad (7)$$

where the angle is measured with respect to the negative Z-axis with a clockwise range to -180° and a counterclockwise range to 180°. Thereby, clinical flexion-extension and lateral bending angles can be calculated respectively using tilt (ϕ) angle and tilt azimuth (θ) angle:

$$F = \phi \cdot \cos(\theta) \quad (8)$$

$$L = \phi \cdot \sin(\theta) \quad (9)$$

where L is positive while left lateral bending (counterclockwise). The real-time rotation angle can be represented by the twist (τ) angle obtained from the current value of the unit vector $p_2'$ as follows:

$$R = \tau = \arctan\left(\frac{2w_2 \cdot y_2 + 2x_2 \cdot z_2}{-2w_2 \cdot x_2 - 2y_2 \cdot z_2}\right) \quad (10)$$

where the range of twist (τ) angle is same as the tilt azimuth (θ) angle from the midsagittal line. The three clinical parameters flexion-extension (F), lateral bending (L) and rotation (R) are used to calculate the angular motion of the trunk. The processed outcomes are then compared with the predefined hazard thresholds for WMSDs prevention. The clinical parameters for head and neck can be determined in a similar way.

## 2.3 Real-time warning threshold algorithm

The real-time warning threshold algorithm in the WIMU-based motion warning system for the prevention of WMSDs is developed to translate the clinically meaningful real-time data into warning triggers when postural hazards are detected. Taking trunk inclination for an example, the according maximum acceptable holding time and hazardous angle of inclination are shown in Figure 4 (ISO 11226, 2000).

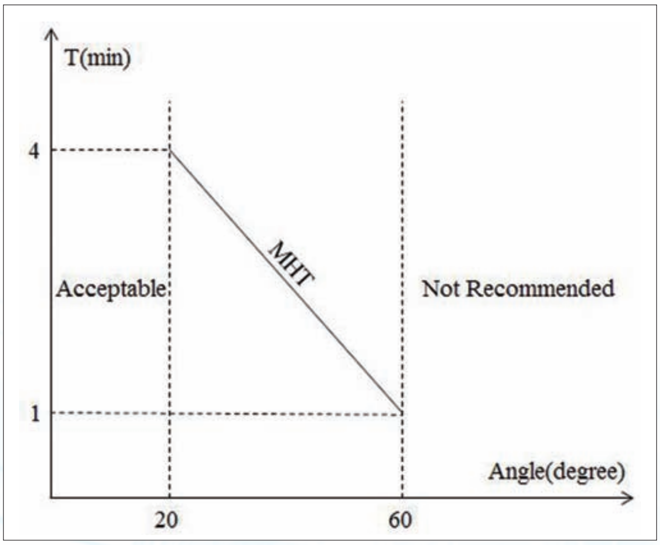


**Figure 4:** Maximum holding time vs. trunk inclination.

The 'Acceptable' zone indicates that the angle of trunk inclination is not ergonomically hazardous. The 'Not Recommended' zone represents a high risk of lower back pains once the angle of trunk inclination is over 60°. Between the 'Acceptable' and the 'Not Recommended' zone, a function between time (min) and static angle (degree) is indicated,

$$MHT(A) = -3/40 \times A + 11/2 \quad (11)$$

where $A$ is an instantaneous angle of a worker's trunk inclination emerging in each output frame at work. According to Eq. (11), the thresholds of maximum holding time of operational postures can be determined.

The basic procedure of the algorithm is to accumulate the entire individual maximum holding time of each real-time angle emerging in each frame to compare with the actual period of operational postures. The real-time accumulated individual maximum holding time (MHT) at time $t$ (s) and nth frame with an output frequency $f = 1/T$ can be approximately calculated as follows,

$$MHT_n = MHT\left(\sum_{i=1}^{i=f\cdot t} A_i \cdot T \Big/ t\right) \quad (12)$$

Previous research revealed that dynamic motions result in longer endurance times than that in static tasks (Law, 2010) so that current MHT calculating method of static motions can guarantee the purpose of preventing lower back and neck pains for workers in both static and dynamic operational postures. The actual period of time in which hazardous postures are detected by the algorithm is determined by $\Delta t = \Delta n / f$ (unit of $\Delta t$: s). Once the actual period $\Delta t$ is larger than the accumulated maximum holding time, the smartphone application will send out an alarm warning, indicating that the current angle of trunk inclination between the 'Acceptable' and the 'Not Recommended' zones has lasted for a period that can significantly increase the risk of WMSDs around lower back pain.

## 3. EXPERIMENT AND VALIDATION

A laboratory test was first carried out to validate the proposed WIMU-based real-time motion warning system with a data capturing rate 10 times per second, which is tested in the following test to be detailed enough, stable and energy efficiency for long-term service. After sensor calibration, the laboratory experimental subject started to do some basic movement in sequence in terms of flexion, extension, right lateral bending, left lateral bending, right rotation, and left rotation in head. These are shown in Figure 5 as an intercepted part of the obtained motion data from our safety management database in the backend server. The red solid line indicates the flexion-extension mode, the green dotted line indicates the lateral bending mode, and the black chain dotted line indicates the rotation mode. The real-time motion of head, neck and trunk captured in the experiment are shown in three plots respectively. The real-time angles of both head and neck are calculated relative to the movement of trunk. After frame 150, the experimental subject only moved his trunk in flexion, right lateral bending, left lateral bending, right rotation, and left rotation. As a result, the trajectories of real-time angles of both head and neck were relatively smooth with minor changes. From Figure 5, the distinct trajectories of real-time angles in flexion-extension, lateral bending, and rotation mode validate the motion data collecting and processing algorithms predefined in the proposed PPE system.

To further validate the practical utility and reliability of the proposed WIMU-based motion warning system, a field experiment on a construction site in Hong Kong were conducted. Two scenarios are shown in Figure 6 (a) and (b). It was reported by the on-site workers involved in the experiment that the proposed personal protective equipment can help them recognize hazardous postures without disturbing their operations. Some of them, especially workers under age of 35, can gradually change previous ergonomically hazardous operational patterns by interacting with the real-time warning system. As shown in Figure 6 (a), the tester used to stoop while lifting, which is highly ergonomically hazardous for lower back. After a nearly one-day break-in period for the tester wearing the proposed PPE, improvement has been made in his operations (Figure 6 (b)), which indicates the effectiveness of the self-awareness and self-management strategy based on the proposed WIMU-based motion warning system for lower back and neck pain prevention.

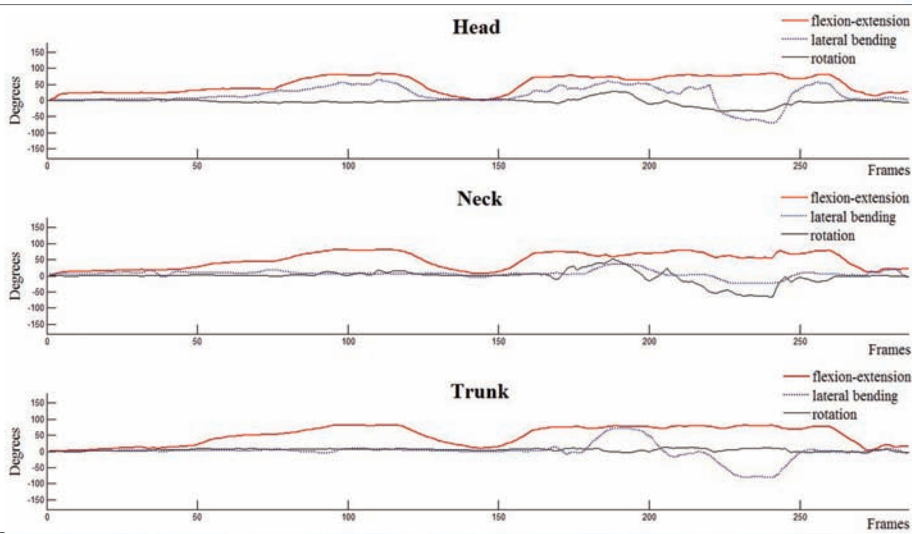


**Figure 5:** Real-time motion data captured by the system.

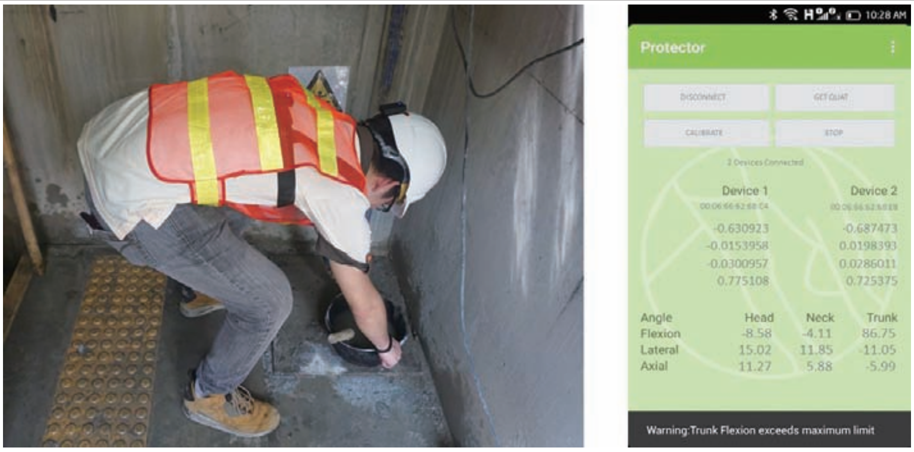


**Figure 6(a):** Break-in period for one tester wearing the PPE in the field experiment.

**Figure 6(b):** Adjustment made by the tester according to the warnings from the PPE.

## 4. CONCLUSION

This paper proposes a WIMU-based real-time motion warning system for construction workers' WMSDs detection and prevention without disturbing their operations. Equipped with the proposed system, the worker can operate normally and be aware of postures that lead to WMSDs around lower back and neck pains. The overall design of the system with respect to sensor arrangement, data collection, transformation, and warning mechanism is illustrated in the paper. In order to collect clinically meaningful motion data, a real-time data process algorithm is developed to transfer quaternion data into real-time angles of flexion-extension, lateral bending, and rotation. In addition, a real-time warning threshold algorithm is also indicated and embedded in the smartphone application for ergonomic hazards detection and prevention. Laboratorial experimentation of the clinically meaningful kinetic data and alarming mechanism are conducted to demonstrate and validate the WIMU-based real-time warning system.

The developed system could have a wide range of applications in almost every work trade exposed to harsh operational environments and high prevalence of WMSDs. In addition, this application can be further developed to be an ergonomic hazard monitoring platform for construction safety managers, from which on-site workers' musculoskeletal health status can be captured and monitored by equipping more IMU sensors with specific requirements. Operational postural data stored in the backend server might also enable developers and safety managers to better analyse the patterns of individuals for more adaptable postural angles and personalized holding time alarming thresholds. The collected data could also be valuable for analysing the relationships between operational workers' behaviour patterns and construction sites' arrangements.

## ACKNOWLEDGEMENT

This research would like to acknowledge the Hong Kong Construction Industry Council (the CIC) Research Fund Project "Waistband Enabled Construction Workers Lower Back Health Monitoring System" and Hong Kong Polytechnic University Block grant "Biomechanical Evaluation and Prevention of Lower Back and Neck Musculoskeletal Disorders of Rebar Workers". The authors are also grateful to the editor and the reviewers for their valuable suggestions.

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Mr. Xuzhong YAN is currently a joint Ph.D. student of Department of Building and Real Estate of the Hong Kong Polytechnic University, and Institute of Construction Management in the College of Civil Engineering and Architecture, Zhejiang University. His research interests focus on construction safety and risk management for ergonomic hazards prevention.

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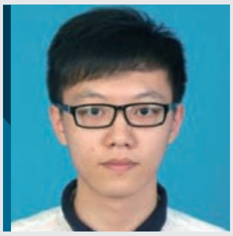

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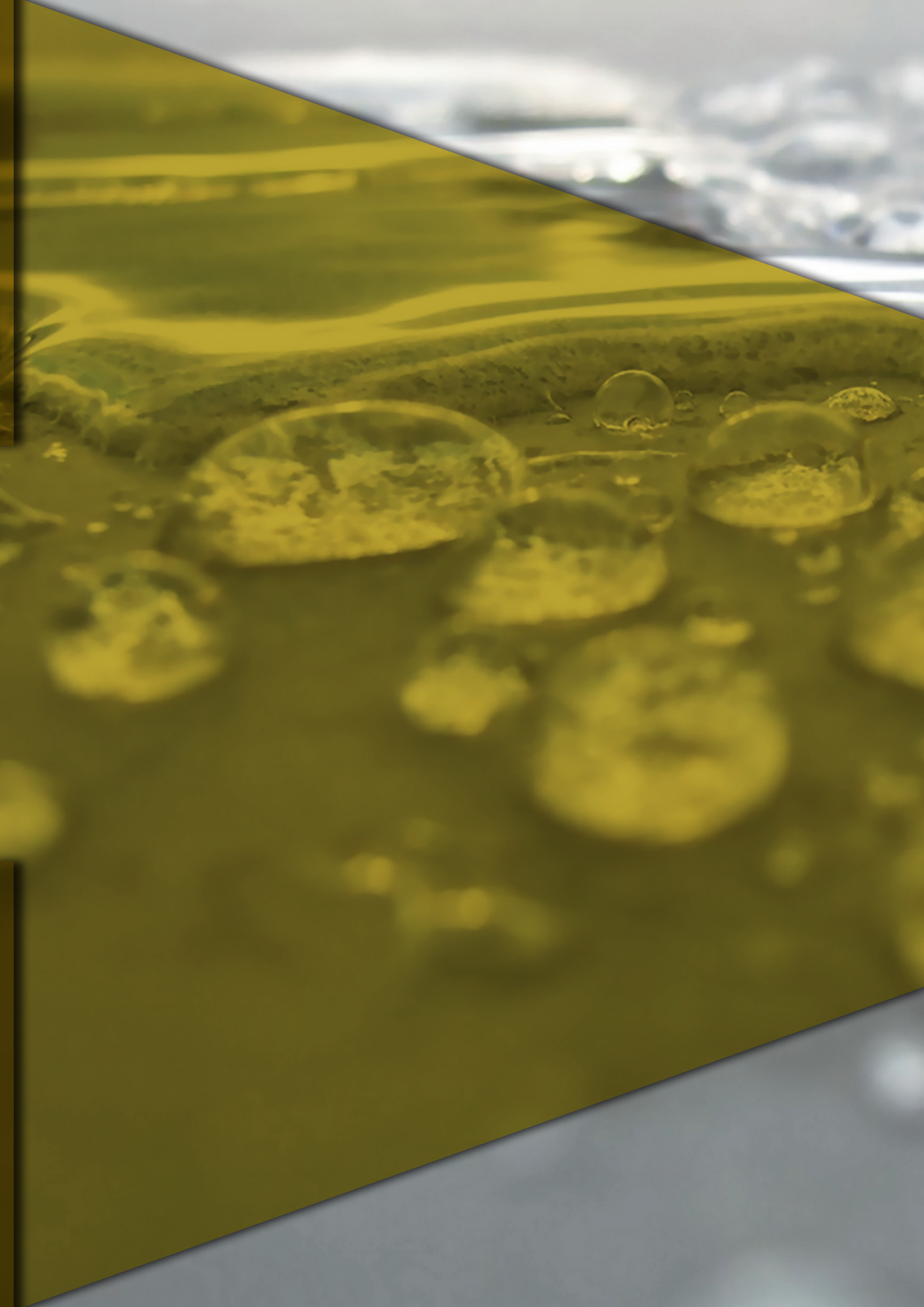

# Waterproofing Application of Sustainable Engineered Cementitious Composites (ECC) with Recycled PET Fibers

# WATERPROOFING APPLICATION OF SUSTAINABLE ENGINEERED CEMENTITIOUS COMPOSITES (ECC) WITH RECYCLED PET FIBERS

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**ABSTRACT**

Water seepage is a common issue of buildings in Hong Kong (HK). To solve the problem, a waterproofing rendering made of Engineered Cementitious Composites (ECC) is developed. Recycled polyethylene terephthalate (PET) fibre and polyvinyl alcohol (PVA) fibre are incorporated in the ECC. The tensile capacity of ECC is over 2%, and the maximum crack width is less than 300 µm. The ECC also reveals water repelling effect and achieves a coefficient of water permeability as low as 4.46 x10-10 cm/s. These results suggest ECC can be very useful for waterproofing applications. Furthermore, by modifying the mix design, ECC can achieve proper workability and good adhesion with concrete substrate, which enable the application on walls. Both lab trial and field trial have been conducted to demonstrate that the ECC rendering can work in practical situations, and has market potential owing to its cost effectiveness.

**Keywords:** ECC; Waterproofing; cementitious materials, polyethylene terephthalate fibre, recycling.

## 1. INTRODUCTION

Water seepage is one of the most severe issues in building management and maintenance in Hong Kong. A poll in HK in 2010/11 revealed that 56% of respondents reported water seepage problem in their premises. There are many causes of water seepage, such as thermal and shrinkage crack formed in concrete, poor concrete quality, deterioration of pipe material, differential settlement, etc. which accelerate corrosion of steel reinforcement and deteriorate the built concrete structure. Therefore, water seepage should not be overlooked, especially for those in basements and water retaining structures because there is always a driving force inflicted by water head difference.

The commonly used waterproofing method is to apply a surface protection layer, either sheet membrane or liquid applied coating, on the concrete surface. When the sheet membrane, for example, bitumen or bitumen-modified sheet, is used, particular attention should be paid on properly sealing the joints between the sheets and ensuring the sheets are not damaged during the subsequent construction process. There are many liquid applied waterproofers, such as epoxy resin, polyurethanes/polyurea and cement-based coatings, which serve as barriers to resist water pressure. Epoxy based waterproof coating can provide an instant barrier, which can harden within a couple of minutes, but its application is hindered by high volatile organic compound level and brittleness. Polyurethane and polyurea have high tensile elongation and ductility. However, they cannot be directly applied on wet surface and bonding to concrete surface is questionable. The application of such waterproof coating is restrained by weather and concrete surface condition. A primer is always needed to improve the bonding between the coating and concrete substrate. Cement-based waterproofing material can offer good bonding to the parent concrete substrate and can be applied on wet surface. However, it has limited elongation and will crack easily when there is a propagating crack in the concrete substrate or differential displacement at a joint.

An ultra-ductile engineered cementitious composite (ECC), also known as Bendable Concrete, has been developed to enhance the durability, resiliency and sustainability of the civil infrastructure (Li & Leung, 1992). At the ultimate state under uniaxial tension, the strain of ECC with polyvinyl alcohol (PVA) fibers can reach 3% to 7% (Li, 2008), with crack width controlled to around 60 μm (Li, 2002), or even 20 μm with properly designed matrix (Yang, Yang, & Li, 2007). The water permeability of cracked ECC has been first studied by Lepech and Li (Lepech & Li, 2009), in which it was observed that the tight residual micro-cracks (about 60 μm) allowed ECC to maintain low permeability similar to that of uncracked concrete even under high tensile strain. Recently, Liu *et al*. ( 2016) have also investigated the permeability of ECC under tension experimentally and analytically, and showed that the permeability of cracked ECC could be estimated as a quadratic function of the tensile strain, instead of the third power of the localised crack width in normal concrete. When ECC is used as a waterproofing layer on the surface of concrete, the high toughness of ECC will cause a propagating crack in the concrete substrate to be arrested (Leung & Cao, 2010; Lim & Li, 1997) and turned into multiple fine cracks with little effect on water permeability. Moreover, tests on freeze-thaw resistance (Li, 2008) and chloride penetration (Sahmaran and Li, 2007) have shown that ECC has excellent durability. With the outstanding properties mentioned above, ECC is potentially considered as an ideal material for waterproofing applications.

According to the annual report issued by the Government of the Hong Kong Special Administrative Region in 2015 there were approximately 206 tons of plastic bottles dumped to landfills every day in 2014, imposing heavy burden on the landfill sites. More than two third of the plastic bottles in Hong Kong are made of PET, a thermoplastic that can be melt and reformed to other shapes. It is desirable to figure out an economical way for recycling of plastic bottles through creating a local demand. In view of the high cost of PVA fibre used in ECC, polyethylene terephthalate (PET) fiber can be an alternative as partial replacement of PVA fibre. Hence, an ultra-ductile cementitious rendering with recycled PET fibre for waterproofing application has been developed.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Materials and Mix Proportion

The matrix for the waterproofing ECC is optimised as listed in Table 1. The matrix materials used in this study are composed of cementitious materials, such as ordinary Portland cement (OPC), calcium sulfoaluminate cement (SAC), fly ash (FA), lime stone powder (LSP), silica sand, waterproofing agent (WPA), shrinkage-reducing agent (SRA) and super-plasticizer (SP). K-II REC15 PVA fibres manufactured by Kuraray Co., Ltd and recycled PET fibbers manufactured by a supplier in the People's Republic of China are employed. The physical properties of the fibres are given in Table 2. The mix proportion is based on a ECC mixed with ultra-high volumes of fly ash developed by the Hong Kong University of Science and Technology (Leung & Cao, 2010). Using high volumes of fly ash results in reduction of steady-state crack width, which is beneficial to waterproofing as well as the long-term durability of the structure (Yang *et al*., 2007). The presence of limestone leads to formation of mono- or hemicarboaluminate hydrates instead of monosulphoaluminate hydrate thereby stabilising the ettringite, leading to an increase in the volume of hydrates, a decrease in porosity and hence an increase in strength (Lothenbach *et al*., 2008). 0.3% WPA and 1% SRA are added in the matrix to offer water repelling effect and to reduce shrinkage, considering that the rendering is applied on a mature concrete substrate.

**Table 1:** Mix proportions of ECC matrix by weight

| Binder (B) | S | W | SRA/ (B+S) [%] | WPA/ (B+S) [%] | SP/B [%] | Fiber (vol. %) | |
|---|---|---|---|---|---|---|---|
| | | | | | | PVA | PET |
| 1 | 0.2 | 0.28 | 1 | 0.3 | 0.22 | 1 | 1 |

**Table 2:** Physical properties of PVA and PET fibers (Tested in lab)

| Fiber | Length (mm) | Diameter (μm) | Aspect ratio | Modulus of Elasticity (GPa) | Fiber Strength (MPa) | Density ($g/cm^3$) |
|---|---|---|---|---|---|---|
| PVA | 12 | 39 | 308 | 16.9 | 1275 | 1.30 |
| PET | 12 | 38 | 318 | 10.7 | 1095 | 1.37 |

All the dry powders were first pre-mixed with fibres in Hobart HL200 mixer for 5 minutes at a low speed to achieve good dispersion of fibre in powder as shown in Figure 1a, then water with SP was added slowly to the dry powders and mixer for another 5 minutes. Figure 1b indicates the uniform dispersion of fibre in the cementitious matrix and good flowability of ECC achieved following the above mixing sequence.

(a) Mixed dry powders (b) Fresh ECC rendering

**Figure 1:** Digital images of ECC

## 2.2 Mechanical properties of ECC

The mechanical properties of the mixtures are summarised in Table 3. Results are given for both 28-day standard curing and accelerated aging which involve additional curing at 60°C for 28 days after standard curing has been conducted. The compressive strength of ECC rendering is higher than 30 MPa at 28-day age, and over 50 MPa after accelerated aging curing. The compressive strength is sufficient for waterproofing applications.

The tensile stress-strain curves of the ECC are shown in Figure 2, for the samples under both 28-day standard curing and accelerated aging curing. ECC with hybrid PVA/PET fibre shows tensile ductility of over 1% for both standard 28-day curing and aging curing. After aging, the tensile strength increases by about 20%, whereas the tensile ductility decreases by around 37%. The change of the tensile capacity of ECC during maturing results from the delicate balance among the properties of matrix, fibres and fibre/matrix interfaces (Lepech & Li, 2011).

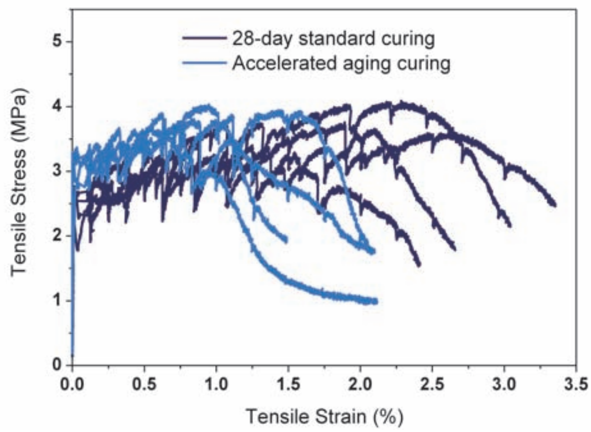



**Figure 2:** Tensile-strain curves of ECC for both standard 28-day curing and accelerated aging curing

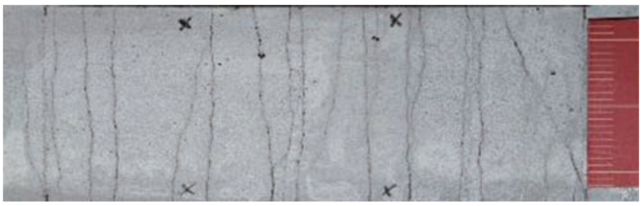
It is known that crack width is highly correlated to water permeability, affecting the durability of the structures. The permissible (surface) crack width in standards or codes is in the range of 200-300 μm. For example, according to the Code of Practice for Structural Use of Concrete (Hong Kong Buildings Department, 2013), the maximum design crack

**Table 3:** Mechanical properties of ECC rendering

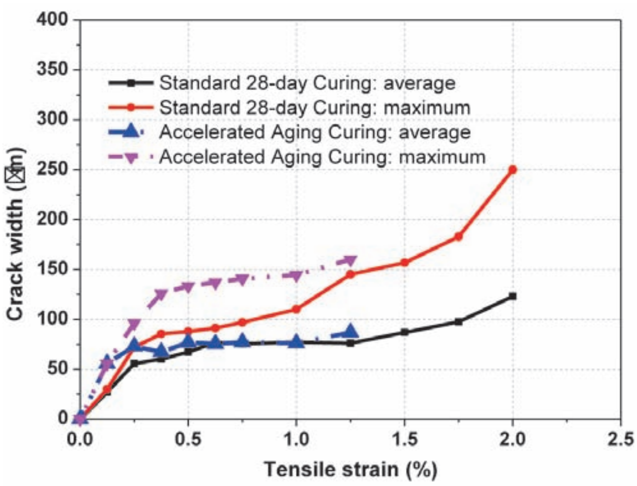
| Standard 28-day Curing | | | | | Accelerated Aging Curing | | |
|---|---|---|---|---|---|---|---|
| Comp. Strength [MPa] | Tensile Capacity [%] | Tensile Strength [MPa] | Bending Capacity [1x10-3/cm] | Bending Strength [MPa] | Comp. Strength [MPa] | Tensile Capacity [%] | Tensile Strength [MPa] |
| 34.37 | 2.16 | 3.63 | 2.53 | 10.10 | 54.58 | 1.35 | 3.86 |

width is limited to 300 μm for normal structures and 200 μm for water retaining structures. Adding reinforcement or minimising reinforcement spacing could help reduce surface crack width. Similarly, adding fibres could reduce crack width effectively as fibres are dispersed into the matrix. The crack width is dependent on the amount of fibres added in the matrix. In this study, the maximum and average crack width of ECC samples are measured by digital image processing (DPI) and the graph of the crack width against tensile strain is depicted in Figure 3. From the graph, at strain of 1.0%, the maximum crack width of ECC is 110 μm at 28-day age and 150 μm after accelerated aging, which are below the limit, showing that ECC could effectively control the crack width.

(a) Set-up of direct tension test with camera



(b) Digital image obtained for crack pattern analysis




(c) Crack width against Tensile Strain

**Figure 3:** Crack width development of ECC for both standard 28-day curing and accelerated aging curing

## 2.3 Waterproofing properties of ECC

A silane-based waterproofing agent (WPA) was added in the ECC rendering to provide hydrophobic characteristics to the matrix. The amount of WPA was taken at 0.3 %. Figure 4 shows water repelling effect on ECC, which is absent on normal concrete.

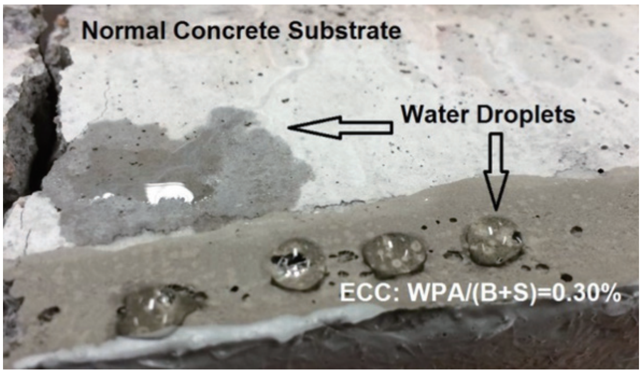


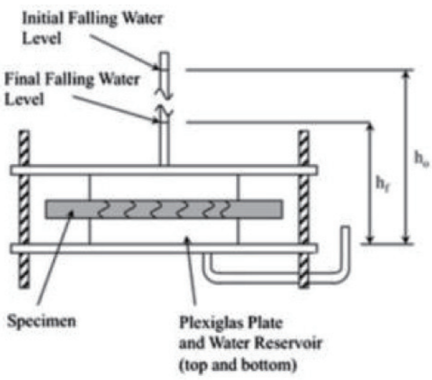

**Figure 4:** Comparison between normal concrete and ECC

Furthermore, water permeability test was conducted. The test setup is shown in Figure 5b, and details can be found in the research conducted by Lepech and Li (2009). The specimen is sandwiched between two water reservoirs and pressure is generated by water in a long vertical tube placed above the upper reservoir. After the specimen is saturated with water (which takes a number of days), the flow is dependent on the water head (h) indicated in Figure 5a. During the test, the height of water in the tube is measured as a function of time. Assuming laminar flow, the Darcy's law can be applied to derive the following equation for calculating the coefficient of water permeability (kw):

$$k_w = \frac{A'}{A}\frac{L}{t} ln\frac{h_0}{h_f}$$

where

A' - Internal area of the tube
A - Area of the sample in contact with water
L - Thickness of the sample
t - Time interval
h0 - Initial water head
hf - Final water head




(a) Falling head setup; (Lepech & Li, 2009)

(b) Testing in laboratory.

**Figure 5:** Water permeability test

The coefficient of water permeability (kw) of the ECC rendering is measured to be 4.46×10-10 cm/s. For normal mortar, the kw value is around 7~8×10-10 (Lepech & Li, 2009). This demonstrates the good resistance of the developed ECC rendering to water permeation, which makes it suitable for waterproofing applications.

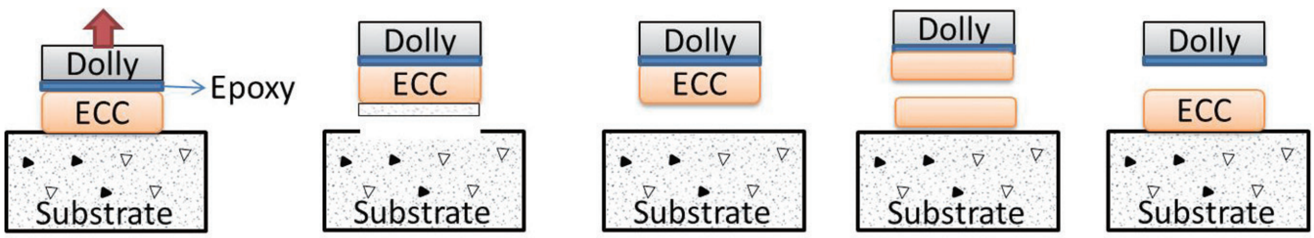
## 2.3 Bond strength

Pull-off tests were carried out to assess adhesion strength between ECC and concrete substrate in tension in accordance with (ASTM D7234-12, 2012). 50 mm diameter dolly is attached on ECC by epoxy. Four possible failure modes are identified as shown in Figure 6.

Results of pull-off tests are shown in Table 4. A control sample is prepared on wet substrate surface and subject to standard curing for 7 days (test 1). The adhesion strength is 0.852 MPa. The adhesion strength on dry substrate surface after air curing (test 2) is 0.306 MPa, which is much lower than that of the control test. This indicates that water on the parent concrete substrate will not affect the adhesion between ECC rendering and concrete substrate, while proper curing will enhance the adhesion. The test 3 studies the compatibility of ECC rendering with commercial top coat. The adhesion strength is similar to test 1 and failure also is found at the ECC-substrate interface, which indicate the good compatibility of ECC-Top coat (ECC-TC) system. To further improve the bonding, polyvinyl acetate (PVAc) is added to the mix. At 7 day curing, the adhesion strength of ECC with PVAc is only 0.463 MPa with the failure surface within ECC, indicating that the mechanical properties have been affected. However, after 28 day of curing, adhesion strength of ECC with PVAc (Test 6) increases to 1.23 MPa which is almost 50% higher than ECC without PVAc (Test 5). This finding suggests that for long-term performance, PVAc should be added.

**Table 4:** Adhesion strength between ECC and substrate under different condition

| Test (3 specimen) | Testing condition | Adhesion strength (MPa) Ave. | Std | Failure mode |
|---|---|---|---|---|
| 1. Control | 7 day curing | 0.853 | 0.039 | b |
| 2. Dry surface | | 0.306 | 0.054 | b |
| 3. With commercial top coat | | 0.833 | 0.09 | b |
| 4. With 1.5% PVAc | | 0.463 | 0.062 | c |
| 5. Control | Test after 28 day curing | 0.865 | 0.005 | b |
| 6. With 1.5% PVAc | | 1.23 | 0.12 | b |




(a) Failure in the substrate
(b) Failure at the ECC-substrate interface
(c) Failure in the ECC
(d) Failure at the epoxy-ECC

**Figure 6:** Possible modes of failure

## 2.4 Workability of ECC

The flow table test in accordance with BS EN 1015-3 was conducted to evaluate the consistency of ECC. The flow diameter of ECC was measured immediately after mixing in order to apply onto the wall; the ECC workability was adjusted to suit vertical application. With w/b ratio of 0.3, a large diameter is obtained, and the ECC falls off the wall. To solve this, w/b ratio is reduced to 0.28, if the w/b ratio is lower than this value, fiber cannot mix well in mortar. Also, PVAc was added at 1.5% into fresh ECC mortar to achieve the right consistency of ECC as shown in Figure 6. Based on the results, it is suggested to use the w/b ratio of 0.28 and 1.5% PVAc.

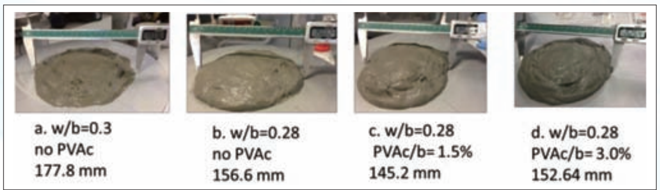



**Figure 6:** Workability of ECC with different mix

## 2.5 Bending flexibility test of ECC-TC

To study the bending behaviour of ECC-TC system, four-point bending test was conducted as illustrated in Figure 7. Four 150 mm x 400 mm x 50 mm (thick) concrete specimens were prepared, in which sample a was directly coated with 1 mm thick commercial top coat; samples b and c were coated with 15 mm thick ECC and 1 mm thick top coat, b was loaded to the failure deflection of sample a and sample c was loaded to failure; sample d was coated with conventional 15 mm thick cement-sand mortar without fiber, and then with 1 mm top coat.

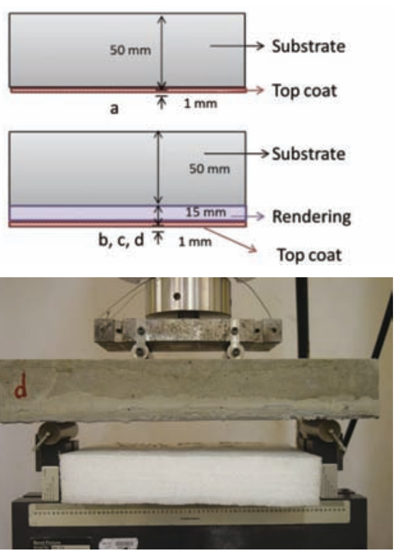



**Figure 7:** Experimental design for bending flexibility test

The results are shown in Figure 8. Sample a and d exhibited a peak load around 5.5 kN, and the ultimate deflection is less than 0.5mm. A single major crack was observed. With ECC rendering, the peak load of sample c increases significantly to 10 kN, and ultimate deflection is up to 2mm. When the single crack propagates from substrate into ECC, multiple cracking can be observed in the ECC.

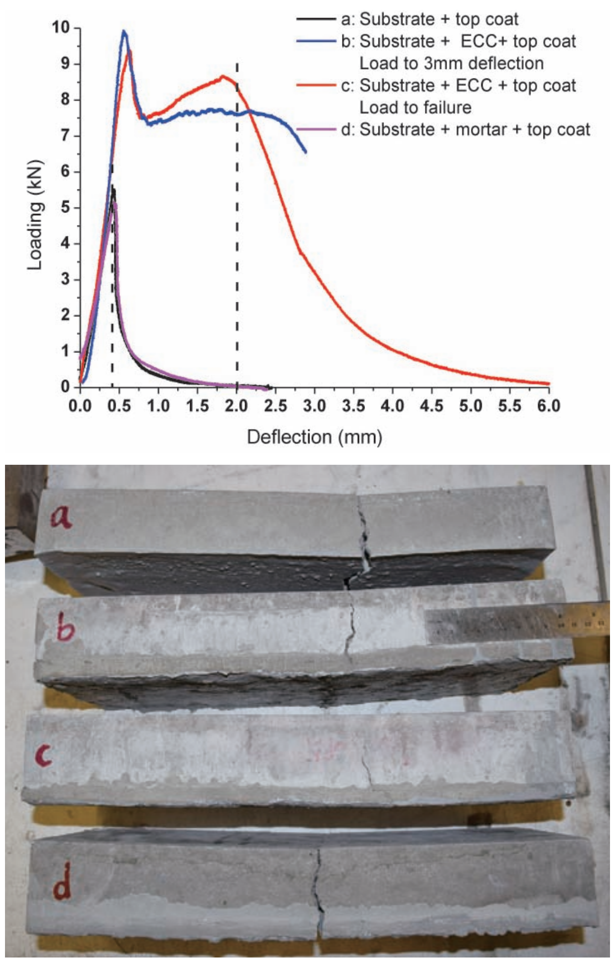



**Figure 8:** Bending flexibility test results

## 3. FIELD TRIAL

Two trials were conducted to evaluate the applicability of the developed ECC rendering. The application procedure is briefly described below and illustrated in Figure 9.

Step 1: Concrete to receive rendering treatment must have a clean and flat surface to ensure maximum bonding, and prevent forming of voids between rendering and roughness concrete surface. Concrete surface will be chiseled by mechanically roughening or high pressure water-jet to 2 to 3 mm thickness. The substrate must be structurally sound, dust-free, and free of grease, oil, dirt, curing compounds, release agents, or any other surface or penetrated contaminants that will adversely affect the bond.

Step 2: Standing water and dust are wiped off from the substrate.

Step 3: ECC can be plastered using a suitable tool. It should be applied from the bottom upwards, and layer-by-layer to achieve the designed thickness. The suggested minimum thickness is 10 mm, and maximum thickness is 20 mm.

Step 4: The ECC surface can be further polished to achieve a flat finish surface.

Step 5: The top coat is applied after 24 hours curing.


**Figure 9:** Application procedures of ECC rendering

A field trial was conducted at a basement of construction site, two 1m x 1m walls with water seepage problems are selected. The application process of ECC rendering is simple, and it can be easily applied on the wall.

(a) Basement Wall Surface (b) In-situ Mixing

(c) Rouged Surface before Applying ECC (d) Finished surface

**Figure 10:** Field trial at a basement

## 4. CONCLUSION

An ultra-ductile waterproofing rendering of ECC with recycled PET fibers is developed. A comprehensive experimental programme was conducted to evaluate the performance of ECC rendering with respect to mechanical property, water repelling ability, water penetration resistance, workability as well as compatibility with concrete substrate and top coat. The ECC rendering shows satisfactory performance in the laboratory tests, as well as ease of application in the site trial.

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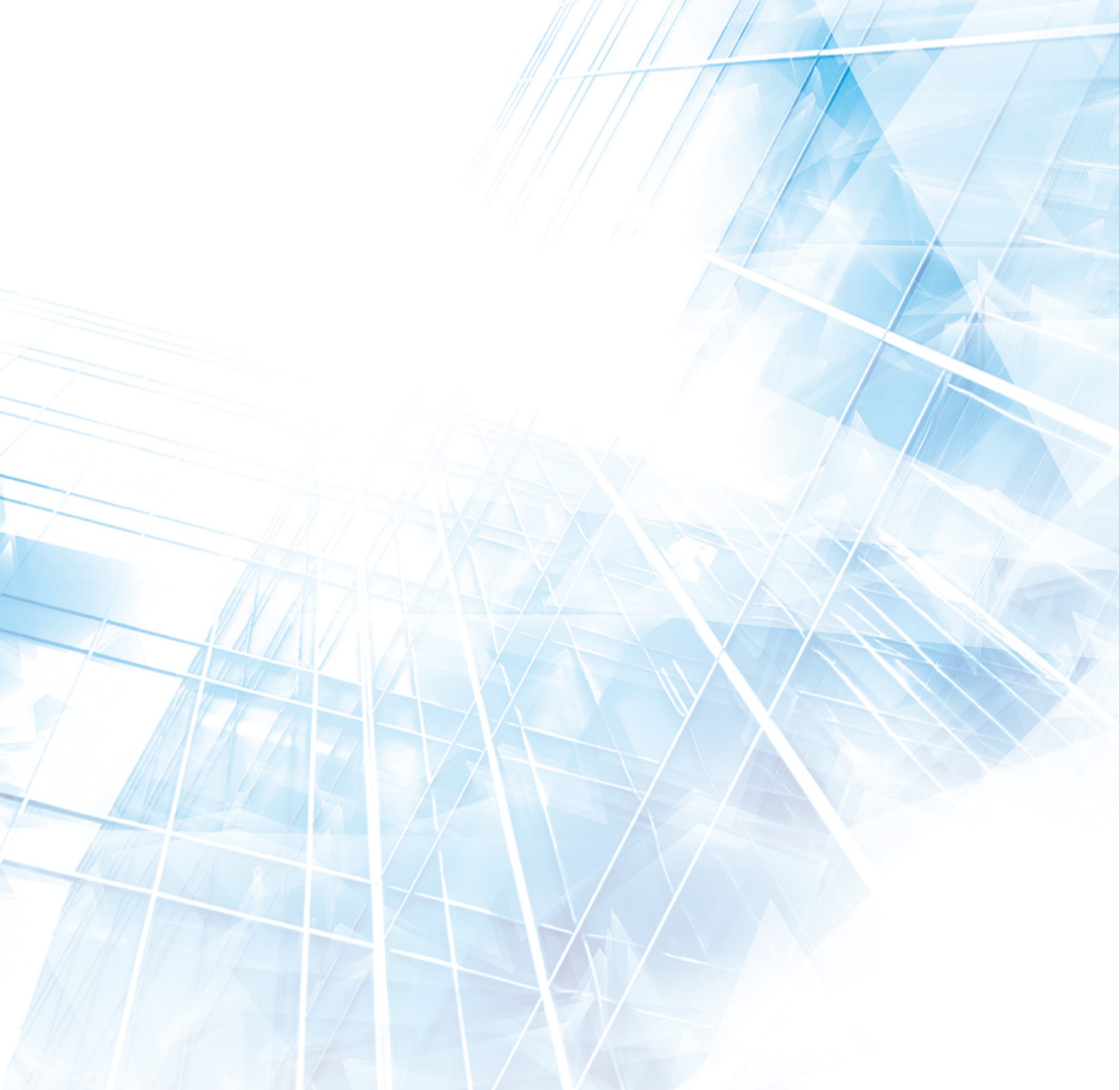


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