CONSTRUCTION INDUSTRY COUNCIL
建造業議會

INNOVATIVE DESIGN TECHNIQUE FOR STEEL-CONCRETE COMPOSITE STRUCTURES IN HONG KONG

RESEARCH SUMMARY

Construction Industry Council
Innovative Design Technique for Steel-concrete Composite Structures in Hong Kong
Research Summary

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FOREWORD

High construction cost have been a major concern in recent years in Hong Kong. The Building Works Tender Price Index, the Civil Engineering Works Tender Price Index and other private tender price indices demonstrated the cost growth was higher than the Consumer Price Index. While number of factors would increase the construction tender price indices, one of the key factors was the materials cost and the construction time.

To reduce the materials cost and the construction time effectively, steel concrete composites have been widely adopted on slabs, columns and beams in many countries for years. While there is lack of analytical tools to meet the Hong Kong design standards, the CIC initiated the research by engaging a research team from The Hong Kong Polytechnic University to develop a simulation-based system for these type of composite.

The research work presented in this report was funded by the CIC Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

The research work described in the report was carried out by a research team led by Prof. Siu-Lai CHAN from The Hong Kong Polytechnic University. The research team had successfully built a software, which was accepted by the Building Department of HKSAR government as pre-accepted structural programme. The project cannot succeed without the dedicated effort of the research team. I would like to thank to all who took part in this valuable work.

Ir Albert CHENG
Executive Director of Construction Industry Council

PREFACE

Steel and steel-concrete frames have advantages over reinforced concrete structures on ease of construction and fabrication, less labour intensive construction activities, lighter weight on foundation and fast speed of construction as the steel frames do not require setting to build up strength against loads. The drawbacks of steel structures such as higher unit material cost and requiring extensive on-site welding are offset by lowering steel cost in recent years and proposed use of bolt connections in place of welding joints in this project. As a result, many advanced countries including U.K., USA and Japan construct more steel-composite structures than reinforced concrete structures to date. In China, this trend is also noticed.

The high building cost and labour shortage in Hong Kong indicate a potential for more use of steel-composite structures which could reduce cost as less workers are required for concreting with most components of the steel-composite frames fabricated in factory across the border to Mainland with extensive use of automatic welding robots. This project highlights the advanced method for economical, safe and efficient structural design of steel-concrete composite structures. The use of bolt joints modelled by semi-rigid connections is studied and the nonlinear method of structural design is developed and discussed. Further, biaxial bending design of composite columns, shear walls and shear walls of arbitrary shape is demonstrated. In conjunction with other research projects by the investigators, software for biaxial bending analysis of steel composite columns and core walls is coded and made available for use by engineers freely.

The objective of this project is to promote better construction and design for the benefit of Hong Kong in the aspects of cost effectiveness, safety, construction speed efficiency and engineering excellence. The investigator believes the modern structural form of steel-concrete composite construction with advanced design method will strengthen these areas for Hong Kong and allow faster and more efficient construction of buildings to meet the high housing demand from its residents.

The investigator would like to express his sincere thanks to the CIC for support of this project.

Ir Prof. Siu-Lai CHAN
Department of Civil and Environmental Engineering
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EXECUTIVE SUMMARY

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

The combined use of composite structures is not new in Hong Kong and has been employed in linking concrete beams to H-piles and steel columns but its application is not materialized. In Hong Kong, many buildings are constructed on small sites with limited areas and sometimes irregular site geometry that reinforced concrete structure is wasteful and expensive in use of land because of huge column size and heavy loads on foundation.

To overcome the problem of labour shortage by using more efficient construction method and, reduce design cost by using composite structures, the composite structures and design are needed to be researched and developed, and this method is generally called the second-order plastic analysis method of design. This efficient design method was not used in the past because of the complexity due to modelling and numerical solutions. To avoid this tedious modelling, engineers normally adopt the less economical and safe method of design called the linear elastic design method. This old method is less safe and uneconomical because it incorrectly calculates the moment and forces of members by ignoring the large deflection and material yielding effects, leading to over-design redundant members and under-design critical members, so the method is both unsafe and uneconomical.

The second-order plastic analysis is a useful tool for practical design and investigation of structural behaviour under ultimate limit states, and has been extensively researched over the past few decades for conventional and performance-based design, studies for progressive collapse, structural fire engineering and so on. In order to accurately model the holistic structural behaviour and stability, the vital effects inherent to a real building are needed to be considered, and these include initial imperfections, residual stress and geometric and material nonlinearities.

The beam-column element analysis method is generally regarded to be considerably more efficient and effective in design of practical framed structures, and extensive research has been conducted since 1970s. Much effort has been made by numerous researchers. Numerical techniques have been extensively used for solution of related nonlinear engineering problems.

This technique using a single element per member not only brings convenience and efficiency in design, but also reduces difficulties of modelling member initial imperfection, which is essential and crucial for safe design using either the second-order elastic or the inelastic analysis.

Initial imperfections are present in all structural members and frames, which significantly affect the stability and strength. The importance of proper modelling of initial imperfections has been reported by the investigator in his earlier publications. The analysis model based on one element per member is highly preferred and considered as a fundamental requirement for practical, efficient and accurate modelling of frames allowing for effects of initial imperfection. The directions of the initial member imperfections are generally set in the same shape as the global buckling mode or the load deflection mode in order to generate the more adverse effects. Consequently, the technique to model one member by several elements not only increases the computational time, but also brings much inconvenience to update of the model in each case of load combination. To this end, the element formulation for modelling the initial member imperfection by one element is desired and proposed in the past decade.

Conventionally, the plastic hinge approach assumes plasticity occurred at a certain short length near the two ends of the element such that the locations of two lumped plastic hinges are assumed at either end and the associated rotational stiffness is deteriorated for simulation of the gradual cross-section yielding. Many researchers have successfully adopted this method for inelastic analysis of steel frames. However, in some circumstances, the plastic hinge could be formed at zone other than the ends of the member. Therefore, two or more elements are required to model each member, which causes much inconvenience in modelling the member initial imperfections and increases computation time.

With this background, a curved beam-column element, which allows plastic hinges to form in an arbitrary location along the member as well as two end zones, is developed to allow the direct analysis more applicable in practical design. Also, the mathematical formulation and modelling procedure for the refined plastic hinge are developed in this project. In order to incorporate directly the proposed element into existing non-linear structural analysis software, the stiffness condensation approach and the generalized external nodal forces are derived and reported herein. Finally, several benchmark examples are employed to validate the proposed theory.

The achievements of this project are summarized as follows.

i. Developed an elasto-plastic design method for composite structures allowing for complex crack and fracture surfaces for concrete;

ii. Formulated a technique for design allowing for semi-rigid connections and for more uses of high-strength bolts than welds;

iii. Derived a rational model for plastic-hinge analysis of composite structures;

iv. Calibrated the accuracy of the methods against experimental test and code formulae and;

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

The work produced in this project makes the engineers' dream of design by simulation without use of prescriptive formulae possible so we could now design structures using any materials economically and safely without constraints by the formulae in design codes. When the work is known and used by engineers, the efficiency and cost of constructing buildings and advanced structures will be greatly enhanced and reduced.

CONTENTS

1 INTRODUCTION

1.1 Background

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

The second challenge is the high construction cost in Hong Kong which is among the highest in the world. It is fair to say that the high construction cost leads to a high safety record in local construction industry, but there should be room of improvement for lower cost and high safety standard. The solution is to make use of technology for refined, detailed and accurate design and computation of structural safety under various load scenarios. In the past, a higher safety standard is achieved by using greater load factors or safety margin via the use of more materials or over-designing the structure because of uncertainty in the old design method. This project allows us to build a platform and design philosophy with various computer programs to achieve the aim of more accurate design and analysis so the response of a structure made of different composing materials can be estimated reliably and accurately. As a result, cost and safety can both be improved.

1.2 Research Aim and Objectives

The aim of this project is to reduce cost of buildings and structures with further improvement in safety standard and productivity. The specific objectives of this project, which are summarised in the following, are to achieve the development of a practical design method.

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

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

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

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

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

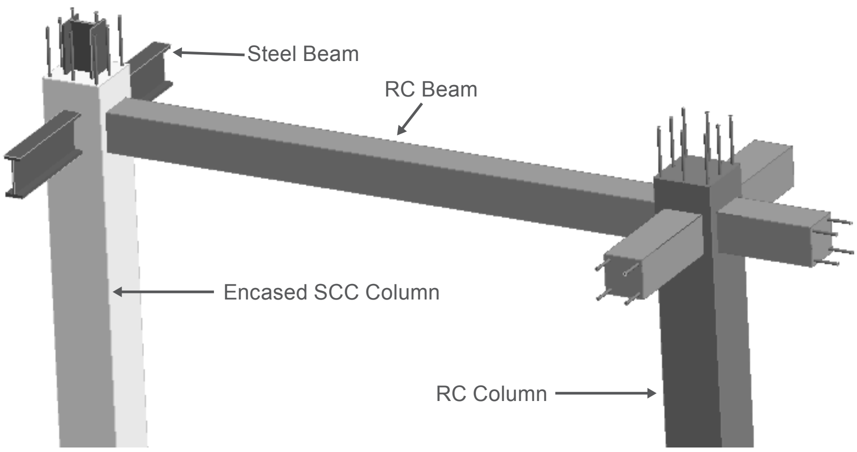

Figure 1(a) Typical composite constructions - Type 1

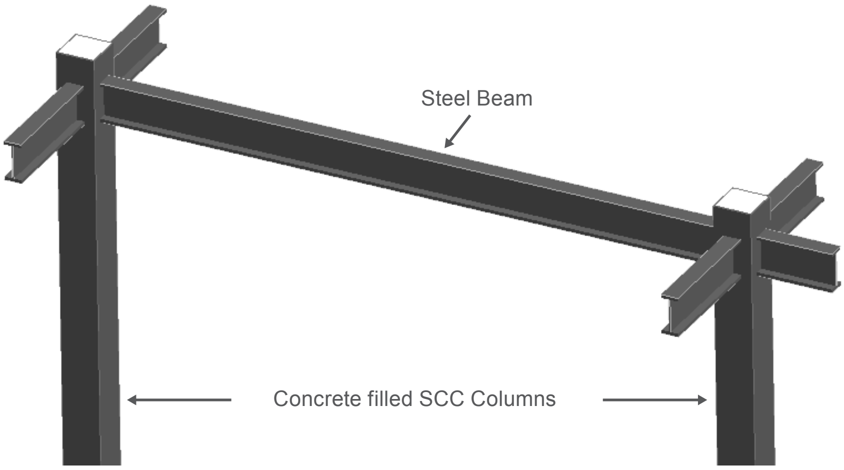

Figure 1(b) Typical composite constructions - Type 2

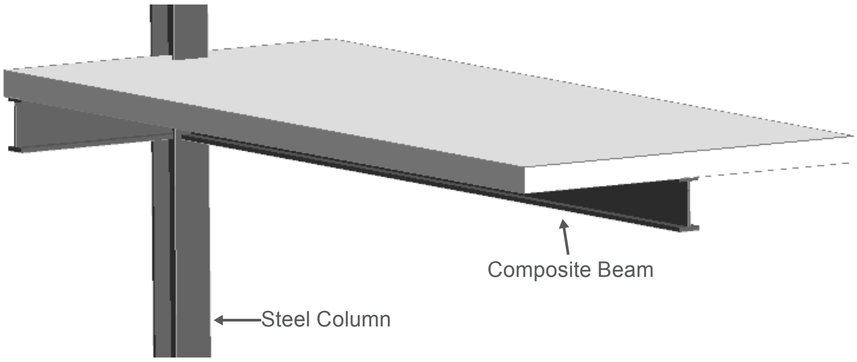

Figure 1(c) Typical composite constructions - Type 3

1.3 Scope

The scope of this project is to develop a useful and practical design method for composite structures. The project developed a new and curved beam-column element with arbitrarily-located plastic hinge for second-order inelastic or direct analysis of steel frames. Unlike the conventional plastic hinge element which requires two and more elements to capture the locations of plastic hinge along member length causing much inconvenience to model member initial imperfection, the proposed element per member is sufficient for an accurate analysis and this makes the design much simpler. The proposed element explicitly models the member initial imperfection allowing for member P-δ effect directly. The plastic hinge is simulated as a gradually softening spring and the corresponding formulae are presented. The additional degrees of freedom in the element are condensed so that the element can be easily incorporated into existing computer programs with dramatic improvement on numerical efficiency and accuracy. The developed design method should improve efficiency in structural design, safety level and economy of building construction.

1.4 Research Methodology

The new design method involves a more complicated procedure and this is possibly one reason why it is not adopted in pre-computer age. With the availability of low cost high performance computers, the design method and procedure can now be easily executed to date.

The analysis and design procedure are summarised in a flow chart below.

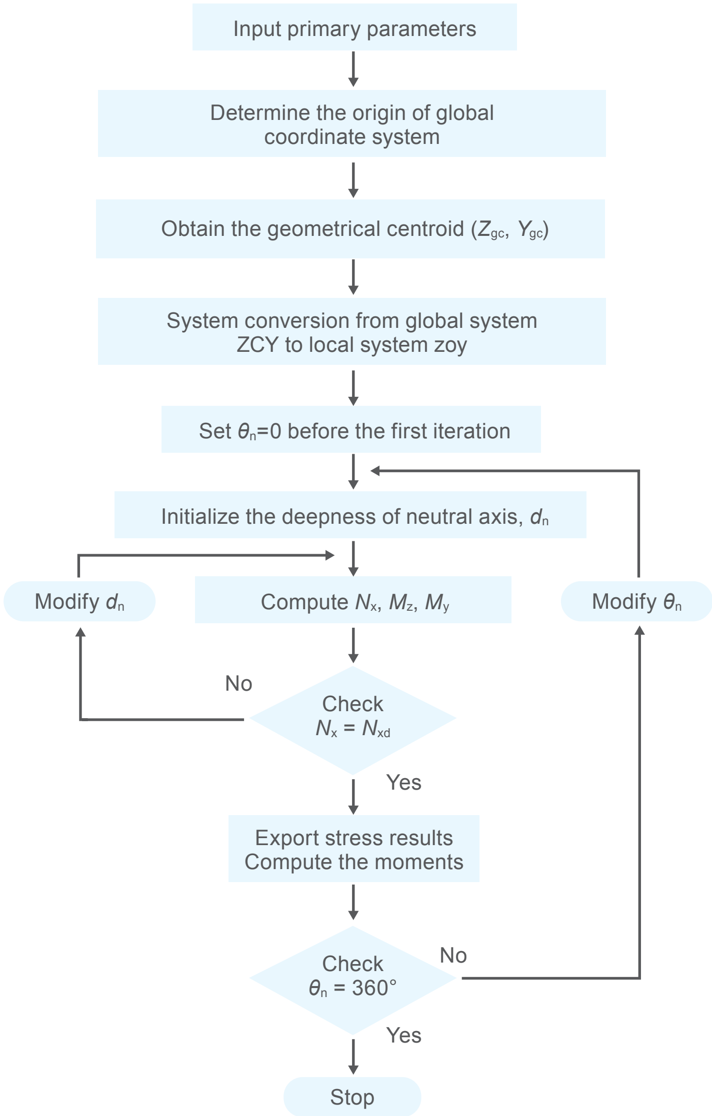

Figure 2 Flow-chart for iteration to obtain resistance of a beam-column

With the information of axial force and moment capacity (N_x, M_y and M_z in the above) obtained in the above iterative procedure, we can determine the load capacity of a beam-columns including shear walls and core walls so we could check the safety of the building. If the applied loads are greater than the resistance, more steel or concrete are needed and, if the opposite as applied loads are much smaller than the resistance, we could reduce the amount of steel and concrete used. In doing this iterative design, the exact amounts of steel and concrete required are calculated instead of estimating approximately by the simplified formulae in design codes. The saving could be very significant and makes our design more economical and safe since the over-estimation of member capacity can be avoided.

1.5 Research Achievements

The following steps were taken for achieving the aims of design safely and economically composite structures.

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

This is the most complicated part of the project and the iterative technique to find the resistance of a beam, column or beam-column is shown in the flowchart in Figure 2. Basically, the technique is to iterate based on a neutral axis inclined to an arbitrary angle with calculation of the axial force and moment resistances about two axes computed to form the ultimate failure and yield surfaces.

2 Formulate design technique allowing for pinned, rigid and semi-rigid connections with more uses of high-strength bolts than welds for saving of manpower and better quality assurance.

The relatively simple spring model for simulation of the stiffness of connections is developed here as shown in Figure 2. Mathematically the spring can be incorporated into the stiffness of a beam-column by the following equations.

The bending equilibrium equations in an incremental form can be expressed as,

$$\begin{bmatrix} \Delta M_{s1} \\ \Delta M_{s2} \end{bmatrix} = \begin{bmatrix} S_{s1} - S_{s1}^2 (K_{22} + S_{s2}) / \beta_s & S_{s1} S_{s2} K_{12} / \beta_s) \\ S_{s1} S_{s2} K_{21} / \beta_s) & S_{s2} - S_{s2}^2 (K_{11} + S_{s1}) / \beta_s \end{bmatrix} \begin{bmatrix} \Delta \theta_{s1} \\ \Delta \theta_{s2} \end{bmatrix}$$

with

$$\beta_s = \begin{bmatrix} K_{11} + S_{s1} & K_{12} \\ K_{21} & K_{22} + S_{s2} \end{bmatrix} > 0$$

and, S_{si} is the stiffness of section spring, ΔM_{si} is the incremental nodal, $\Delta\theta_{si}$ is the incremental nodal rotations, K_{ij} is the stiffness coefficients of the element. The original beam element can be transformed to element with springs at two ends to simulate connection with finite stiffness.

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

In the new and rational model for design of composite structures, the behaviour of the structure is modelled directly rather than assumed empirically. For example, figure 3 is an illustration of the design, analysis and checking of the safety of a simple building.

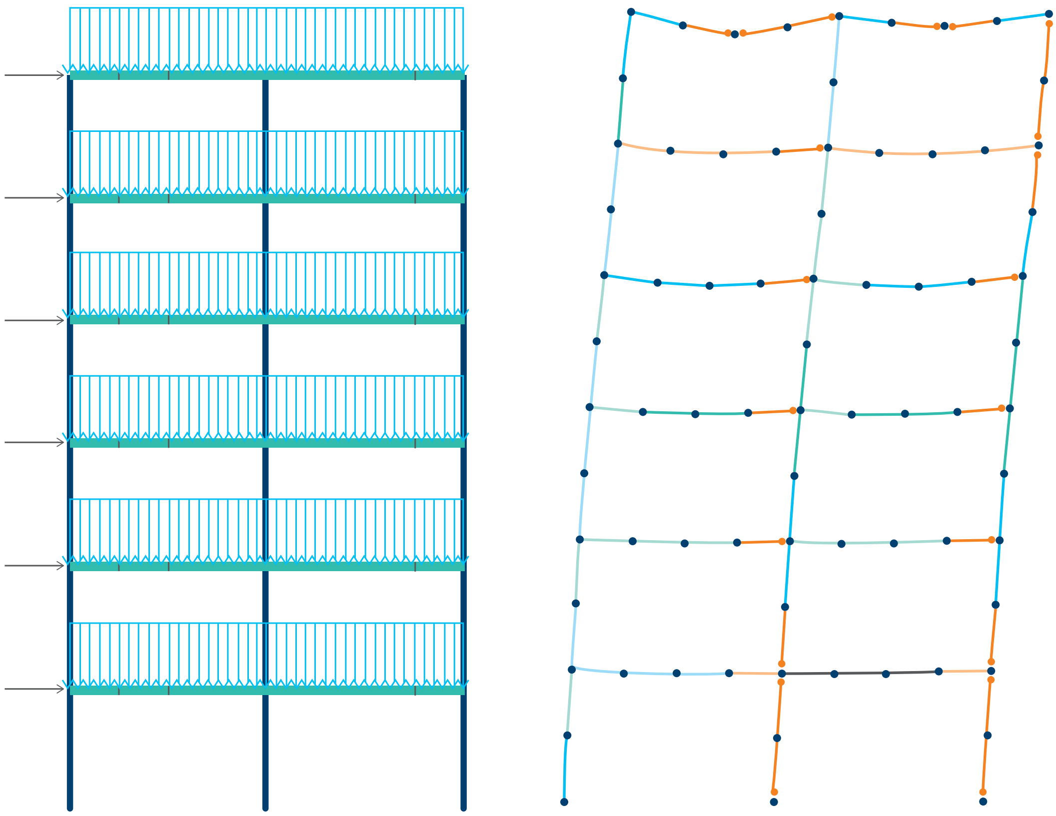

Figure 3 Original layout of a 6-storey building before and after loading
(Left : before loaded, Right : after loaded with plastic hinges shown as orange spots)

From the Figure 3, we could design the building by inspecting its stability and safety directly, rather than relying on empirical formulas which consider only element design but not their interaction in a frame as above.

4 Verify the accuracy of the methods against experimental test and code formulae

The accuracy of the method has been compared with many tested structures such as the one below. The method is verified to be reliable and accurate. Figure 4 shows the frame before tested, Figure 5 indicates the computer model in this project and Figure 6 is about the verification of experimental and theoretical results. The new method is verified to be reliable and practical in these exercises.

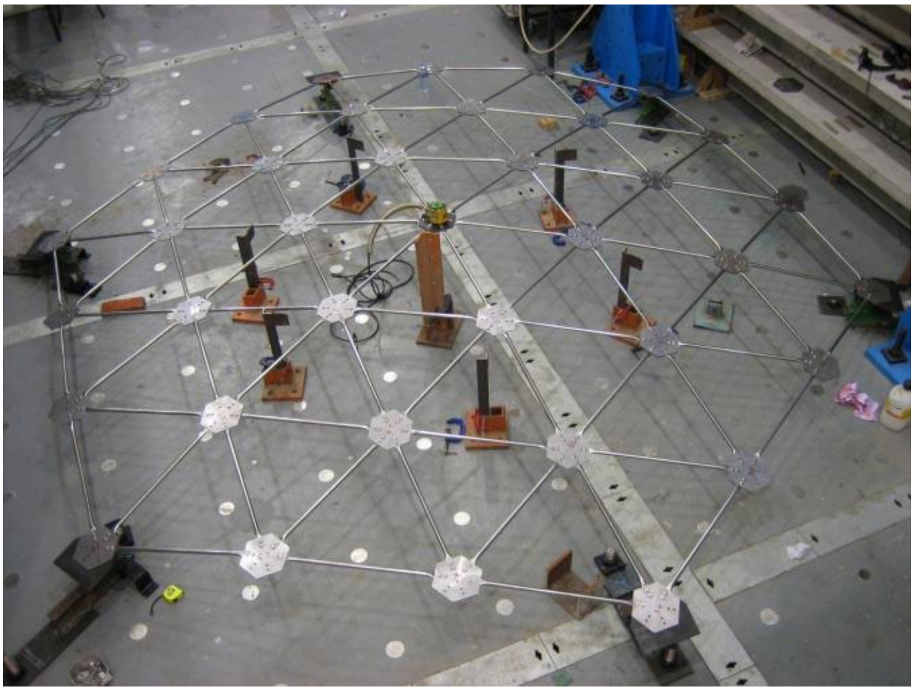

Figure 4 The dome before test

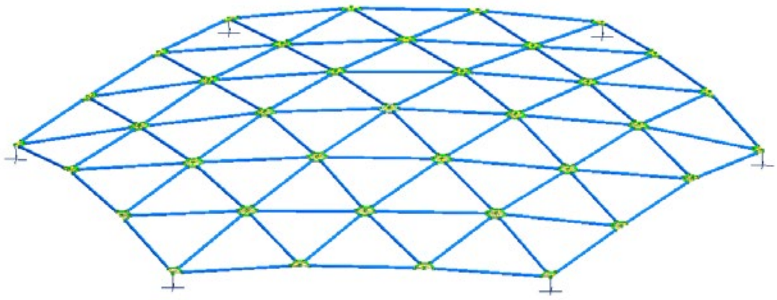

Figure 5 The computer model in the software developed in this project

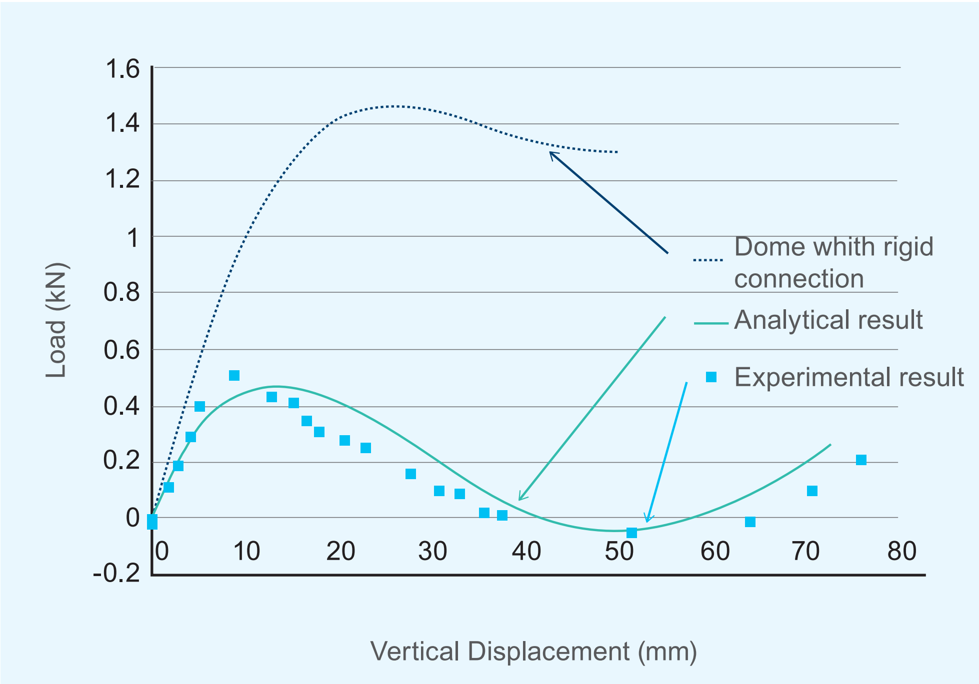

Figure 6 Comparison of test and theoretical results

2 RESEARCH FINDINGS AND DISCUSSION

2.1 Introduction

Construction cost in Hong Kong is the highest in the world and labour shortage is another problem in the construction industry. To address these issues, we could transform the construction method from the traditional reinforced concrete structures to advanced composite structures so less bar-fixing is required and more steel and composite structures are adopted. Steel-concrete structures take the best characteristics of steel and concrete materials for production of an efficient structural form. Many structural benefits can be found in a hybrid steel and concrete framed structure, which is usually superior to the traditional steel and reinforced concrete constructions in regard to the cost-effectiveness, constructional efficiency, seismic performance and so on. However, the current design and analysis practice for this structural form is complicated, inconvenient and inconsistent. Moreover, the initial imperfections including the global frame imperfection and the local member imperfection, which are important factors affecting structural stability and force-distributions, cannot be properly presented and modelled in the conventional analysis approach. To alleviate the drawbacks, a new and superior design and analysis methods for the hybrid steel and concrete members and frames are explored in the present research.

This concept looks simple but the reason why it was not adopted in the past is because the design of composite structures is too tedious by the formulae in code which also contain many restrictions including regular shape and symmetrical placement of steel sections etc. In Hong Kong, most columns and core walls are irregular so these code equations could hardly be used.

This project proposes a unified second-order design and an efficient advanced analysis method for hybrid steel and concrete framed structures that can deal with the analysis and design of irregular shaped core walls and columns. Herein, a curved beam-column finite element with arbitrarily located plastic hinge was developed for simulating large deflections and inelastic behaviours of planar and spatial frames. Further, a robust cross section analysis technique based on the quasi-Newton numerical scheme is developed for arbitrary sections. Sequentially, three types of sectional yield surfaces are generated for evaluating the sectional strength and a refined plastic hinge model combined with these surfaces are given for various types of members. With these formulations, the unified design and analysis approach requiring only the fundamental material constitutive models is developed. In addition, an experimental investigation on the use of high-strength concrete (HSC) in the concrete-filled composite construction is carried out. Extensive numerical examples have been employed from the available literatures and experiments for verification of the accuracy, reliability and practicality of the proposed analytical methods, and several design cases are also adopted to demonstrate the application of the proposed approach.

2.2 Principle

Hybrid steel and concrete framed systems are a new structural form combining the advantages of concrete and steel. The common types of hybrid steel and concrete framed structures are illustrated Figure 7 below, which may consist of bare steel (BS), reinforced concrete (RC) and steel-concrete composite (SCC) members.

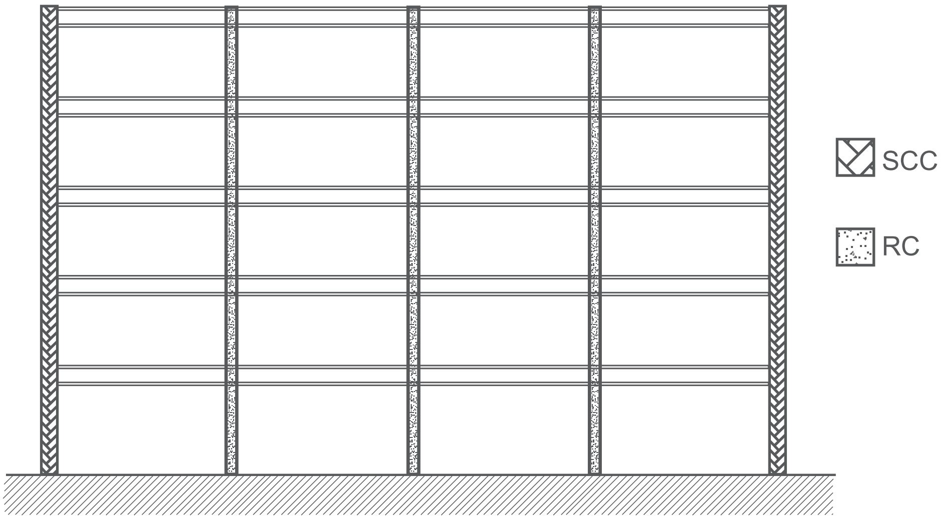

Figure 7 A typical composite building

Many structural benefits can be found in a hybrid steel and concrete framed structure including the structural efficiencies in terms of strength, stiffness and ductility and cost-effectiveness with the optimal use of materials according to their mechanical characteristics. For example, concrete has high compressive strength, large damping ratio and good corrosion resistance, while steel possesses high-tensile strength, excellent ductility and efficient constructability. Previous studies showed that for the hybrid constructions, besides time-efficient construction process could be achieved, the concrete components usually offered considerable damping properties to the whole structural system, while the steel components with light self-weight could reduce the foundation cost.

Besides the member strength checks, the flexural buckling of axially-compressive members and the overall stability of framed structures are always concerned in both analysis and design. The initial imperfections and the P-δ effects are vital for the individual column buckling and further affect the overall-system stability. In the past, due to the limitation of the computer technology, the design practice is mainly based on the hand calculation associated with the linear elastic assumptions. In order to consider the buckling effects, Euler (1759) firstly derived a buckling equation for a theoretically isolated and perfectly straight column under different boundary conditions. Since then, a stability design method by assuming the column effective length determined by the related K-factors had been proposed and still widely adopted until now. Later, the Perry-Robertson formula was derived by Ayrton and Perry (1886) and Robertson (1925) based on the Euler's buckling equation (1759) with consideration of the initial member imperfections; and a series of buckling curves for different values of imperfections were obtained and adopted in most of the design codes and guidance since then.

With rapid development of computer technology, the traditional first-order linear design approach is gradually recommended to be replaced by the second-order nonlinear design method. Second-order design method, which is also called direct analysis method in the AISC (2010) code, is a numerical and simulation-based approach. In this design method, the P-Δ and P-δ effects and the initial imperfections for individual members and the complete frame are directly considered in analysis. Member-local and frame-global stabilities can be accurately reflected in the analysis process, and as a result the assumption for the effective length by K-factors is eliminated.

In the current design practice, separated codes for design of members made of different materials are referred to. For example, Eurocode-2 (2004) is employed for RC members, Eurocode-3 (2005) for BS members and Eurocode-4 (2004) for SCC members. This brings much inconvenience and sometimes confusions to the structural engineers. Although the descriptions for stability design in the steel, concrete and composite codes may be different, the requirements for consideration of second-order effects, such as P-Δ and P-δ effects and the initial imperfections, are conceptually the same. It is noted that the P-δ effect is commonly ignored in most previous research and therefore the tedious member buckling strength check by codes is still needed. To this, a unified design approach for the hybrid steel and concrete systems is needed to be investigated for both design efficiency and analysis accuracy.

In the second-order analysis design approach, as the P-Δ and P-δ effects and the initial imperfections have been directly reflected in analysis, the member strength can be simply evaluated by the cross section check at its critical locations. However, different types of sections can be found in a hybrid steel and concrete frame, such as reinforced concrete, single or built-up steel and encased or in-filled concrete composite sections shown in Figure 8. In order to calculate the sectional capacities of these sections, the complicated and tedious formulations in codes for various types of sections are still required. Therefore, a robust and generalized cross section analysis technique for arbitrary sections is necessary to be explored.

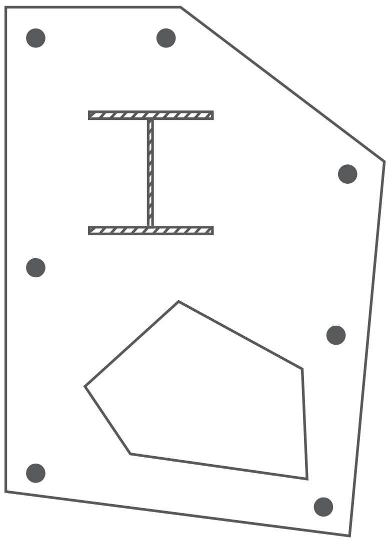

Figure 8 An irregular column with elements of I-section, reinforcing bars and concrete

The philosophy of the advanced analysis approach is to accurately reflect the structural behaviour inherent to a real structure, and therefore, various effects are needed to be considered such as initial imperfections, concrete cracking, geometrical and material nonlinearities. Moreover, advanced analysis approach is a fundamental tool for performance-based seismic design, progressive collapse simulation and the failure limit state analysis, and it is useful for investigating the system performance under other extreme event or rare cases. Due to the mechanical properties are significantly varied between the steel and concrete, an efficient and practical advanced analysis approach is required to be investigated.

The use of concrete-filled steel tube (CFT) columns are increasingly popular in the modern structures, especially for the high-rise buildings. However, their applications are commonly limited to typical sectional shapes such as the rectangular or the circular. When one needs to design the uncommonly shaped tubular sections, the existing codes such as Eurocode 4 (2004) do not provide adequate design formulae and provisions. Furthermore, the specified concrete grades as in Eurocode 4 (2004) are ranged from C25 to C60 for the composite construction, and therefore, the utilization of high strength concrete (HSC) in steel tubular columns is needed to be analysed by experimental studies.

In summary, unified second-order design and practical advanced analysis methods for hybrid steel and concrete framed structures are explored in this project. In addition to this novel design and analysis approaches, an initially curved beam-column element with capacity of simulating large deflections and high inelastic behavior was formulated. To avoid the tedious formulae for various types of section capacity checks, a robust cross section analysis technique is developed for arbitrary sections composed of concrete, steel reinforcement and steel components. Moreover, a generalized plastic hinge model for the hybrid steel and concrete members is also needed to formulate. The distinct feature of the present study is that an efficient curved beam-column element is derived in conjunction with an accurate cross section analysis technique, where only the basic material constitutive relations are required in both design and analysis.

2.3 Findings

In this project, the advantages of using composite structures in place of bare steel or reinforced concrete structures are explored and the advanced second order direct analysis method is developed to be able to design the complex structural form. Using more steel material is user-friendly as can be seen in China, Japan, UK and USA. As labour and land cost in Hong Kong is very high, using more steel to reduce labour works is justified. Further, composite structures normally are lighter and involves lower foundation cost. Taking all these into account, the overall cost for composite buildings could be lowered than reinforced concrete buildings. The finding of this project provides engineers a competitive alternative in choosing of building materials and structural form, and there will be more performance-based design that engineers only need to demonstrate the adequacy of his structural system against different requirements and scenarios.

The objectives of this project are to propose a unified second-order design approach and a practical advanced analysis method for the hybrid steel and concrete composite structures for improvement in productivity and efficiency. Due to the mechanical characteristics being significantly different among various material types of structural members, a new beam-column element is needed to be formulated for simulation of all these vital factors. Similarly, a robust cross section analysis technique is needed to be developed for arbitrary sections. The constitutive models are crucial for both the analysis and design and a proper input of the related material properties is a prerequisite for a reliable analysis and design.

Hence, the research findings are summarized as follows.

1) Proposed a new beam-column element with the allowance for initial member curvature and capability for simulating large deflections and inelastic behavior. Under some circumstances, the plastic hinge is likely to form along the member length rather than its ends, especially for a beam under uniformly distributed loads. Therefore, an arbitrarily located plastic hinge within a member can be allowed in the proposed element.

2) Developed an analytical model for advanced analysis by one element per member and this can significantly improve the numerical efficiency as well as the reduction on modeling efforts. In order to achieve an efficient nonlinear analysis, the numerical solution methods are explored and studied.

3) Developed an accurate and robust cross section analysis technique for arbitrary sections in a hybrid steel and concrete framed structure. Various material constitutive models are capable to be considered in analysis. Moreover, different sectional states such as concrete fracture, initial yield and ultimate failure limits need to be evaluated accurately in the proposed method.

4) Extended the refined plastic hinge model for various material types of structural members in a hybrid steel and concrete frame. Since the conventional plastic hinge model is mainly developed for analysis of BS members, the extension of this model to other types of members are needed to be explored.

5) Introduced a unified and practical second-order design approach. The recently published codes, such as Eurocode 3 (2005) and Eurocode 4 (2004), have recommended the direct use of second-order analysis in design practice. A study on the use of these codes is required. Several examples are selected and analyzed by the proposed method and the conventional linear approach for comparisons.

6) Studied the proper inputs of the material constitutive models. Since the material properties play an important role on the accuracy in analysis, and therefore, a study on these constitutive models mainly based on Eurocodes is carried out. As the Eurocode 4 (2004) only permits the use of normal strength concrete in concrete-filled composite construction, the material behavior of high-strength concrete (HSC) in steel tubes is needed to be experimentally studied.

7) Proposed a practical and efficient advanced analysis approach for the hybrid steel and concrete frames. A series of benchmarking examples from literatures and experiments are selected for verification of the proposed method.

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

A number of research papers were published with support of this project. These papers report the technical problems and methods to solve them so we could now design and construct more composite buildings as a new page for Hong Kong.

2.4 The Value and Impacts of the Project Outcomes on the Construction Industry

This project proposes a new structural scheme with a new design method that could change the culture of labour-intensive construction to semi-automation of construction for composite buildings. This improves the productivity of construction industry in years to come so the construction industry in Hong Kong could become more knowledge-based. The speed of constructing safer and more economical buildings can be improved in years to come.

Steel-concrete composite structures are common in seismic and non-seismic countries like Japan and U.K. The reason is lack of and high cost in manpower in doing bar-fixing, and Hong Kong seems to be facing a similar problem.

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

(1) Productivity will be enhanced and manpower or construction works will be reduced with less steel bar fixing works;

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

(3) Higher ductility against dynamic and cyclic forces like seismic loads and smaller member size leading to smaller loads on foundation;

(4) Lighter member size leading to more usable area and;

(5) More economical and sustainable design by accurate evaluation of capacity of structural members.

2.5 The Achievements of the Specific Research Objectives

As seen in Figure 7, mixed frame structures composed of steel, concrete and composite members are widely used to-date due to their structural efficiency as alternatives to traditional steel or reinforced concrete systems, especially in high-rise buildings. The design of this form of structures is inconvenient as it needs several separate design codes for steel, concrete and composite elements.

This project proposes a nonlinear design method which only requires section capacity check without the use of different codes for the mixed frame structures besides the eliminations of any linear-analysis-based assumptions for the second-order effects. The project makes much improvement to the design and construction of composite structures as reported in a series of research papers in the topic. In summary, we can now design and construct composite building with a much lower weight of steels and with shorter period of construction time. Further, the process of progressive collapse in case of extreme event like explosion can be studied and simulated with risk determined. Due to the fact that membrane forces, which allowed a redistribution of internal forces, can be activated additional bearing capacity of the structure could be achieved. In the past, an economical design of an irregular column such as the ones in Figure 8 is difficult and tedious, but this project develops an advanced interactive scheme to determine the moment and axial force resistance easily, reliably, efficiently and accurately. This structural form may not be common overseas where space is abundant, but it is popular in Hong Kong where building design is controlled by straight area plot ratio so architects and engineers commonly construct irregular columns to suit the site conditions. All we need when using the theory developed in this project are basic material properties and dimensions of the column without use of simplified axial force – moment curves which are limited to regular and symmetrical column shape so the design is direct and accurate.

To consider material yielding on the overall behaviour, the refined plastic-hinge is further developed for the analysis of the composite and reinforced-concrete members by introducing the yield surfaces of the section. In generating the yield surfaces of the cross section, the nonlinear stress-strain constitutive relationship is assumed for concrete and steel materials. The compression zone of the concrete section is divided into adequate number of segments and the entire structural steel section will be meshed into small fibres in order to adopt the various stress-strain models for determining the section capacity of arbitrary shape reinforced concrete or composite member subjected to axial force and biaxial bending. Once the initial and fully yield surfaces are determined, the gradual yielding can be simulated by the proposed refined plastic-hinge method.

3 RECOMMENDATIONS

Efficient structural design is important for continuous development of Hong Kong which needs to house millions of people in the coming decade. Therefore, productivity is an essential issue for engineers. The developed nonlinear analysis method of design in this project is much more accurate than the linear analysis simply because the former gives more detailed consideration of material yielding, instability and buckling which lead to structural failure. To date, occasionally a nonlinear analysis is carried out for safety check but it is seldom used for direct design such as member sizing, and this shows the limitation of the current nonlinear theories applied to practical structural design. This project developed a new nonlinear design concept, theories and techniques for structural design in the next century as a move from principally linear analysis to nonlinear analysis using I-cloud computing which allows efficiency in computer-time and storage extensive computation. The proposed nonlinear theory will make nonlinear analysis a primary design process, rather than a secondary check currently used in the design practice adopted by structural engineers.

3.1 Putting the Work to Design Codes and Publications of Design Guidelines

This immediate extension is to allow the work produced from this project to appear in design guides and codes so engineers can see the procedure of using the new technology. The investigator has record of putting his research to design codes which include not only the local code, but also the overseas codes including the ones in USA and Europe. The next step after this project is to publish not only research papers which are useful in confirming the validity of the theory checked by the international peers, but also to publish design guides to train and educate engineers to adopt the new method. Seminars and conferences will be organized for the purpose of allowing more engineers to be known of the advantages of the new method.

3.2 Development of Cloud-based Technology for Building Design

Another future extension of this project is related to the situation in Hong Kong and the region. Labour shortage in construction industry including structural design offices has been an acute problem in Hong Kong which is required to build many high-rise buildings for its people and migrants in the coming decade. At present, structural engineers in Hong Kong carry out their design by personal computers of modest capacity using the linear analysis with checking by design charts in codes which may be assisted by excel spreadsheet for easy manipulation of data. This process is inefficient and normally leads to over-design of some members and under-design others. A cloud-based computer tool using the performance-based nonlinear analysis for design of steel, composite and concrete structures and in fact any type of building materials is to be developed project. Theoretically speaking, if one knows about the material properties, geometric properties including imperfections and characteristic loads, he could design a structure within a certain confidence limit safely by the finite element analysis. To date, one can predict the behaviour of a complex structure using a powerful and widely accepted finite element packages such as ABACUS, and ANSYS but seldom a steel or concrete structure is wholly designed by these packages in design office, because structural engineers do not have a set of parameters such as models of residual stresses and geometric imperfections of practical structures for input to these finite element packages which use types of finite elements more suitable for refined and detailed finite element stress analysis such as for aircraft and car design rather than for building design. Further, these powerful packages are not designed or coded for dealing with hundreds of load scenarios in buildings and structures so their use is less convenient. Another major difference that makes the finite element package appropriate for automobiles but not for conventional building design is that the former requires a very detailed analysis with many material properties known in detail. As for building design, structural engineers adopt various factors in design codes for variation of material properties and loads and they need to complete a design within a short time frame, especially under the Hong Kong local condition. Thus, efficient and reliable design element accounting for various practical features such as residual stress and geometrical imperfection is required to be developed from this project. These element technologies and properties require the basic stress-strain properties of the material under cyclic and static load and also the imperfections of members and global structures built from the materials. Innovative and intelligent uses of these properties are required for quantifying the safety of the structures under estimated loads. Unfortunately, current design uses one code for one material such as concrete code for reinforced concrete structures, steel code for steel structures, composite code for composite structures etc. for their design. This approach suffers many disadvantages. For example, engineers need to use several codes for design inconveniently and, more importantly, it hinders the innovative design as combined used of materials in a single building may not be covered by any single code and also uses of different codes contain inconsistencies such as material factors and material grades adopted in these codes. If a single universal code can be developed based on basic material and structural properties and parameters, much convenience can be gained and engineers are free to use combination of materials to produce more economical and safe structures. The reasons for not adopting this approach in the past are due to lack of nonlinear theory for practical design, powerful computers and cloud computing platform which could deal with simple structures by moderate computers and complex structures by renting of computing time for super-computers and lack of technology in nonlinear analysis of practical structures stipulated in recent design codes such as the more open and advanced American and Eurocode series requiring design of unavoidably imperfect structures. I-cloud computing platform allows easy share of technology and cooperation and also permits the use of super-computer for real-time analysis of mega structures with its computer time rented from big computer centres in the USA and China such that the present project is believed to be feasible for a medium size city like Hong Kong which may not be justifiable to maintain and operate a super-computer.

In future work, the design theories, element technologies and computer tools developed by the investigators will be modified to cover various aspects of structural design which mainly covers the aspects of actions from wind, seismic with materials as bare steel, steel-concrete composite and reinforced concrete structures. Super-computer-based nonlinear design for mega structures and real time simulation with an I-cloud platform making use of fast computer speed and memory for structural simulation will be extended. I-cloud technology has been used in many fields but relatively less in civil and building engineering and this technology is particularly useful in building design where simulation needs super-computers of which the service is now available in some big super-computing service providers in China and USA. Using the latest technology in super-computers, we can design structures under seismic, wind or fire attacks much more efficiently and reliably to meet the need of modern societies. The rental computer time is suitable in medium city like Hong Kong as we save cost in updating the supercomputer technology which is unjustified in our applications but will certainly be maintained in these big countries at least for their weather forecast application where super computer is needed. Uploading and running the software for run in I-cloud should be feasible by the team whereas the biggest challenge and originality will be the development of a set of nonlinear structural design theories for replacement of linear analysis and design based on codes without any unsafe outcome for a single load case or scenario.

3.3 More Uses of Advanced Composite Construction

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

The key issues for materializing the proposed new structural form under conventional load cases and unconventional scenarios like fire, seismic engineering and progressive collapse due to accidental damage of structural members rely on development of a computer method. This project develops a reliable computer-based design approach capturing the buckling behaviour and material yielding. Efficient computer modeling in the analysis software is needed as it not only saves computer time, but it also makes the model simple and consistent with the current model for a linear, old or traditional analysis which suffers from the lack of sufficient information after yielding and significant deflection occurs in a structure. The researcher has also successfully developed an element capable of capturing the essential characteristics for elastic-plastic buckling (see Zhou and Chan, 2004) and the element needs to be refined for yielding with unloading. This change of design concept is a non-trivial task as many structural analysis and design programs are still based on old element like the Hermite cubic element ignoring initial and load-induced curvature, because the old element is assumed always straight in its formulation.

3.4 Advanced Design Concept – Structure Robustness against Progressive Collapse

Robustness in structural engineering is a measure of the resiliency of a building structural system in the face of natural and man-made hazards. Accidents due to gas explosion in kitchen etc. should not lead to the complete collapse of the building and robustness is the ability of the structural system to arrest a local failure in order to avoid a complete system collapse. Robustness issues have been brought to the forefront of contemporary structural engineering research and practice as a result of several high profile progressive collapse failures that occurred in the past decade, which include the collapse of a series of canopies in U.K. as well as the collapse of Twin Towers in New York decade ago. In future, we could develop simplified and practical models based on beam-column, shell and discrete spring finite elements to simulate the overall response of a structure. The work can be extended to seismic design of structures to investigate the significance of damage of structural members due to earthquake loads and detailing in improving the progressive collapse resistance of building structures. Studies on connection models and member models will be needed to investigate the behaviour of the structure subjected to collapse condition. The study requires an efficient and fast scheme to perform the analysis for highly nonlinear problems, concerning geometry, material and changing boundary conditions such as contact. Finally, development of design recommendations for robustness will be published and introduced to engineers for safer construction of buildings and structures.

In spite of extensive research, the structural engineering community has yet to reach consensus regarding how to ensure robustness of the building infrastructure. Three primary reasons are to blame. The first one is that there are few design documents worldwide that can be used to attain robustness of new and rehabilitated structures. The second reason is related to an almost complete lack of experimental results that characterize member and joint responses under collapse loading. For example, there are very few publicly available test results of composite floor systems in resisting a loss of a supporting column, as well as test results of joints subjected to large deformation accompanied by tensile loading (commonly known as catenary tension) as occurs under collapse conditions. The third primary reason is that the computational simulation demands posed by the collapse problem challenge the best modelling tools. The simulation requires inelastic, large-deformation and contact/impact modelling. This project will bring together an international consortium of leading experts in the areas of collapse modelling and testing to address the three hurdles mentioned above, focusing, on steel buildings.

In conjunction with to robustness design of buildings, the investigation of progressive building collapse is a widespread structural failure initiated by local structural damage, or a successive collapse which propagates from a damage of a relatively small portion of the structure to the adjacent members through the structural frame. It can be also characterized by a disproportionate failure of the structure following a loss of a structural element which is loaded beyond its capacity and fails. This is a dynamic process wherein a collapsing system continually seeks alternative load paths in order to survive. The central philosophy of fail-safe or damage-tolerant design is that the damaged structure should still safely carry the design loads. This aim is achieved by employing structures with many redundancies.

4 CONCLUSIONS AND THE WAY FORWARD

There is no doubt that the economy of Hong Kong relies much on construction and the contribution of our professionals to local economy is to construct safer, more economical and robust structures which are not prone to damage or failure. The problems facing in Hong Kong construction industry include labour ageing and shortage, high construction cost and limited land resulting in construction of highly irregular buildings. This project produces some useful and innovative ideas of simulation-based system design to calculate accurately the response of a building under various load cases to assess and ensure safety in replacement of the traditional approach of using the prescriptive formulae for member design of regular and simple members. It has been used with success on a number of projects in Hong Kong, Macau and Mainland for design of complex structures beyond the scope of the old prescriptive formulae.

The next step forward is to train more engineers to use the new design concept, to put the guidance to design codes for legal use of the method and to carry out more research in various advanced topics such as robustness design to show the advantages of the new concept. Obviously, the design concept can be extended to seismic and fire engineering design which are too complex for application by the old member-based and prescriptive design method. The ultimate aim of this project is to enhance the productivity and technical level of the construction industry in Hong Kong via using advanced design technology and concept, together with the computer methods for simulation-based design of steel-concrete structures.

5 PUBLICATIONS

These papers below acknowledge the support of the CIC for this project.

Journal Papers:

1. Si-Wei Liu, Yao-Peng Liu, and Siu-Lai Chan (2014). Direct analysis by an arbitrarily-located-plastic-hinge element: Part 1: Planar analysis, *Journal of Constructional Steel Research*, 103, 303-315.
2. Si-Wei Liu, Yao-Peng Liu, and Siu-Lai Chan (2014). Direct analysis by an arbitrarily-located-plastic-hinge element: Part 2: Spatial analysis, *Journal of Constructional Steel Research*, 103, 316-326
3. Tian-Ji Li, Si-Wei Liu, Siu-Lai Chan, (2015). Cross-sectional analysis of arbitrary sections allowing for residual stresses, *Steel and Composite Structures*, 18 (4), 985-1000

Conference Papers:

4. A new codified theory of second-order direct analysis for steel and composite structures-from research to practice. 11th International Conference on Advances in Steel and Concrete Composite Structures Tsinghua University, Beijing, China, December 3-5, 2015. - Keynote
5. Direct analysis by an arbitrarily located plastic hinge element, Eighth International Conference on Advances in Steel Structures, Lisbon, Portugal, July 22-24, 2015
6. Stability design of imperfect steel and composite frames, Eighth International Conference on Advances in Steel Structures, Lisbon, Portugal, July 22-24, 2015
7. *Second-order plastic analysis of steel frames by a single element per member allowing for arbitrarily located plastic hinge*, The Pacific Structural Steel Conference (PSSC 2013), Singapore, 8 - 11 October 2013. - Keynote

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