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Frontier Technologies in Steel and Composite Structures

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ABSTRACT

This paper addresses the future technologies in steel and composite structures in order to deal with the challenges of infrastructure development in the future. With the increased urbanisation of the world, the demand on building ever taller structures and longer bridges is increasing. Furthermore, the need to build and maintain the transport and urban infrastructure that allows the world to ensure that this rapid urbanisation is able to be achieved is ever present. The World Economic Forum has projected that annually there is a $1 trillion spending gap or deficit on infrastructure spending each year.

This paper will outline what measures can be taken in the area of Steel and Composite Structures to ensure that this infrastructure gap is bridged. The paper will highlight the advances in materials particularly in the area of steel and concrete and their composite assemblages. The use of innovative structural systems and their ability to rethink, reduce, reuse and recycle from previous approaches of construction is also addressed in detail. The paper also introduces the concepts of structural health monitoring and how they can be deployed in steel and composite structures to make them more efficient. In addition, the concepts of structural reliability and how it can be used both on an elemental level and system level and further deployed in structural updating will also be highlighted. The paper concludes with thoughts on future/frontier research in the area of steel and composite structures to achieve the aim of addressing our future infrastructure needs.

1. INTRODUCTION

The World Economic Forum has identified the concept of the Global Infrastructure Gap. The global demand for infrastructure is estimated at $3.7US trillion annually. This demand however is not being met and there is only about $2.7US trillion being invested each year. This results in a global infrastructure investment gap of $1US trillion annually. Furthermore, in addition to this investment gap, the existing asset base is ageing, (World Economic Forum, 2014).

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Giving an individual national perspective, Australia's population is expected to grow from 23 million to 38 million by 2050 and our cities are set to almost double in size, meaning that the freight task facing the nation will double by 2030. Infrastructure is needed to keep pace with these changes, and it has been estimated that it is necessary in the next 10 years to spend at least $760AU billion on infrastructure, (Business Council of Australia, 2013). The current Federal Government has committed to $50AU billion in Infrastructure spending this year and expects that in the next decade $125AU billion of public and private infrastructure investment will be generated. Thus, even with the current commitments, public funding of infrastructure will need to be extremely efficient and prudent and any measures that can improve priority setting will be of the highest imperative to budget holders and decision makers. One of the key reforms in infrastructure development that is required is to use government budgets innovatively, through the use of smart infrastructure applications (Australian Government: Infrastructure Australia, 2013). To date, there have been many small investigations on aspects of this problem, but as stated by Roos et al. (2004), *"Next generation infrastructure requires a holistic perspective which includes organizational and contextual factors in addition to technical factors as an integral part of the design process"*. Next generation infrastructure will therefore require frontier technologies and this paper will address some of these in the context of Steel and Composite Structures, namely Advanced Materials; Innovative Structural Systems; Structural Health Monitoring and Structural Reliability.

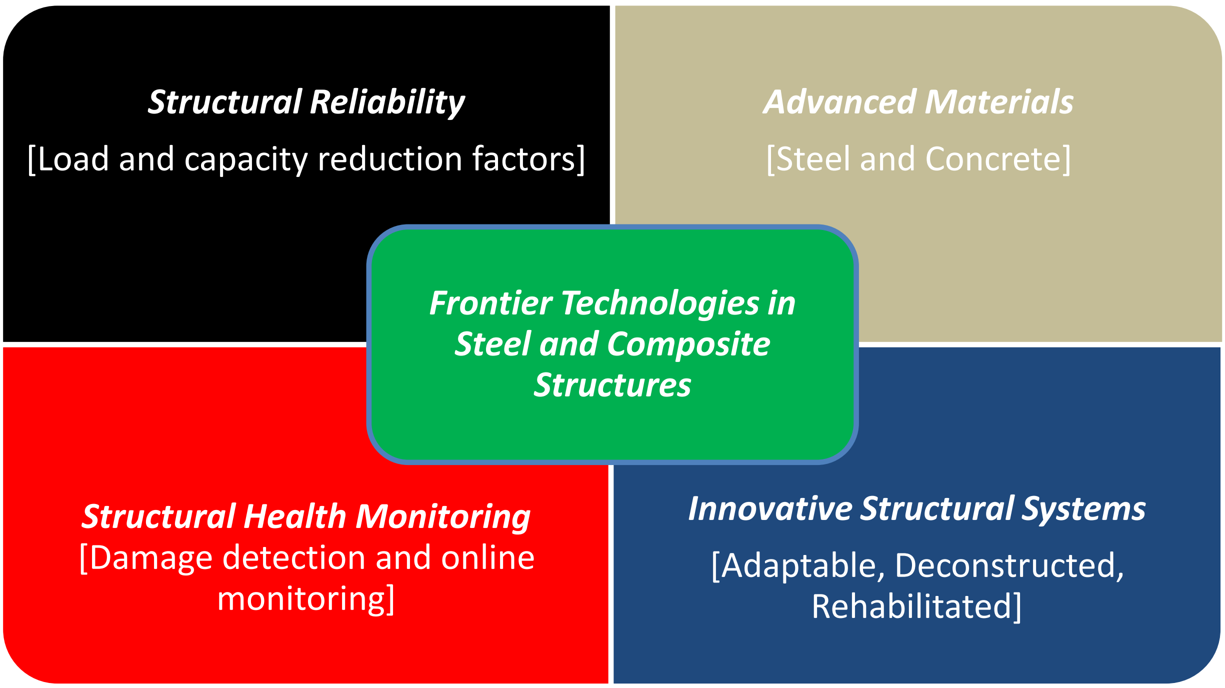

Fig. 1 Frontier technologies in Steel and Composite Structures

2. ADVANCED MATERIALS

The major advances in steel and composite structures have been happening at the advanced material level with the development of high performance steel and concrete which have further optimized the development of composite structural forms. A summary of advances in the steel and concrete fields is provided herein.

2.1 Steel

There has been significant development in the area of high performance steel and high strength steel over the last two decades. The benefits of high strength quenched and tempered steel are best being applied in structures such as long span bridge and tall buildings where weight savings can have a significant offset to the increased fabrication costs associated with the use of fabricated specialty steels.

Hagiwara et al. (1995) and Mochizuki et al. (1995) considered the behaviour of high strength structural steel for the application in super high-rise buildings in Japan. These studies considered the reliability inspection and the welding process for heavy gauge steel plate. Sivakumaran and Yuan (1998) considered slenderness limits and ductility of steel sections fabricated with high strength steel with nominal yield stresses between 300 and 700 MPa respectively. Uy (1999) and Uy (2001a) presented the results of steel and composite sections using high strength structural steel of nominal yield stress 690 MPa. A theoretical model to predict the axial strength of these columns was provided and shown to be in good agreement with the models suggested by Eurocode 4. Uy (2001b) conducted an extensive experimental programme on short concrete filled steel box columns, which incorporated high strength structural steel of Grade 690 MPa. The Eurocode 4 approach, which employs the rigid plastic analysis method, was found to over predict the strength of the cross-sections. A modified technique known as a mixed analysis was therefore developed and found to be in good agreement with both the test results and the refined analysis procedure. This model considers the concrete to be plastic and the steel to be elastic-plastic and provides a much more realistic design approach for sections utilizing high strength structural steel, particularly when large flexural loads are present. Mursi and Uy (2004, 2006a and 2006b) carried out further experimental work on high strength steel slender columns loaded uniaxially and biaxially and looked at the applicability of existing codes of practice to deal with high strength steel and normal strength concrete. Their findings showed that existing codes of practice were quite conservative with dealing with these structural forms, however due to limitations in test equipment capacity this could not be extended to the use of high strength concrete.

More recently Khan et al. (2016) carried out research on the residual stress development of very thick welded high strength steel plates. This research illustrated that the residual stress results of previous research carried out on single pass welded structures may be unconservative when applied to thick welded plates. The study considered plates of 16 mm nominal thickness and were carried out in neutron diffraction testing facilities in the Australian Nuclear and Science Technology

Organisation (ANSTO). More recent research has also been conducted on both short and slender concrete filled high strength steel composite columns. Steel box columns were fabricated with high strength steel sections of nominal yield stress of 690 MPa. These sections were filled with high strength concrete of greater than 100 MPa, (Khan et al, 2017a and 2017b). These tests further illustrated the applicability of current design approaches for the use of both high strength steel and high strength concrete, which are being typically used in the world’s tallest buildings, such as Taipei 101 (Shieh et al. 2003) and Lotte Tower (Kim et al. 2015).

Fig. 2 Taipei 101, Taipei, Taiwan (Shieh et al, 2003)

The other area of significant advancement in specialty steels is in the use of stainless steel for the use in major structural applications such as buildings and bridges. Some of the landmark structures that have used stainless steel sections in composite forms, include the Hearst Tower in New York (Fortner, 2006) and the Stonecutters Bridge (Vejrum et al. 2009). Significant research into the benefits of the use of stainless steel in conjunction with concrete has been carried out by Uy (2008) to illustrate the benefits of the stability and ductility of high performance steels. Uy et al. (2011) then carried out a very detailed study on the short and slender column behavior of stainless steel columns filled with concrete. This study considered both circular, square and rectangular concrete filled steel columns, which have direct application for building and bridge applications.

Fig. 3 Hearst tower, New York, USA (Fortner, 2006)

2.2 Concrete

Sustainable concrete in a high strength form has recently been produced using geopolymer concrete or high volume fly ash (HVFA) concrete. Yazici (2007) showed that ultra high strength concrete of compressive strengths up to 170MPa could be produced by replacing Ordinary Portland Cement (OPC) with pulverized fly ash, granulated blast furnace slag and silica fume. Duxson et al. (2007) also showed that so-called green concrete could be produced with the same qualities as high strength concrete using alkali-activated aluminosilicates to replace OPC. Khatib (2008) showed that compressive strengths in excess of 65MPa could be produced by using greater than 40% OPC replacement. Nugteren et al. (2009) also reported the development of high strength geopolymer concrete with compressive strengths exceeding 100MPa using pulverised fly ash as an OPC replacement. Papayianni and Anastasiou (2010) also reported the production of high strength concrete (compressive strengths exceeding 70 MPa) using high volumes of industrial by-products such as fly ash and slag to replace OPC. Recent research by Noushini et al (2017) also established the stress-strain characteristics for geopolymer concretes which are now being favoured internationally for their low carbon qualities over cementitious concretes.

3. INNOVATIVE STRUCTURAL SYSTEMS

This section will review innovative composite techniques, demountability and rehabilitation of Steel and Composite Structures.

3.1 Composite techniques

In addition to advanced materials, the development of innovative structural systems which improve construction, ensure adaptability and promote deconstructability are criteria that are increasingly sought. These types of systems which allow for demountability and rehabilitability will ensure that the future needs of infrastructure construction and maintenance are met. Some salient examples in modern steel and composite frame construction include the use of spiral welded steel tubes and precast hollow core concrete slabs. Both these systems improve the constructability by promoting off site construction practices which lead to improved efficiency, greater quality and superior safety, (Aslani et al. 2017 and Uy and Bradford, 2017)

Fig. 4 Spiral welded steel tubes, Perth Tower, Australia

Fig. 5 Precast hollowcore units, Sydney Domestic Airport Carpark, Australia

3.2 Demountability

Demountability of steel and composite infrastructure has been the subject of significant interest over the last decade. In Australia, recent examples of this concept include the Olympic Stadium project in Sydney completed in 2000. The end stands of this stadium were made demountable using innovative blind bolts and the structural steel was reused to upgrade the WIN Stadium in Wollongong.

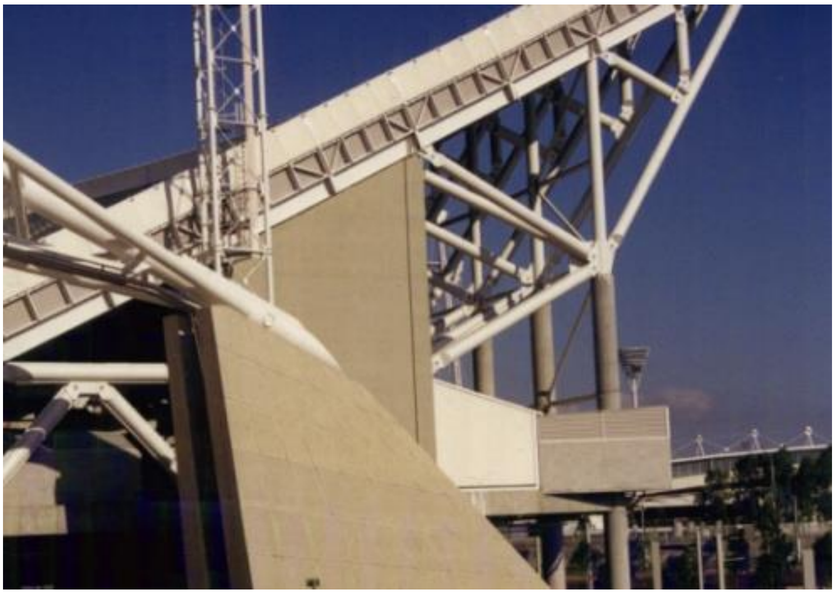

Fig. 6 Sydney Olympic Stadium demountable end stands, Sydney, Australia

Research in Europe, has been ongoing to develop demountable connections for steel and steel-concrete composite buildings, (Brekelmans and Bijlaard, 2000). In the United Kingdom, WellMet2050 is a program centred at Cambridge University focussing on sustainable materials which particularly advocates for the reuse of metal components without melting them, (Allwood and Cullen, 2012). Significant research has been ongoing in Japan into the reuse and dismantling of steel buildings. Fujita and Iwata (2008a) firstly identified a reuse system of building steel structures and they expanded this to look at the key aspects of dismantling and evaluation of the performance of reusable members, (Fujita and Iwata, 2008b). Significant research in Canada into the reuse of structural steel has been ongoing since 2006. This work was funded by the Enhanced Recycling Component of the Government of Canada Action Plan and the Canadian Institute for Steel Construction. The research looks at the specific issue of reuse and recycling for the design of steel buildings, (Gorgolewski 2006). In the United States of America one of the most significant recent examples is the newly opened gift shop on Liberty Island, the home of the Statue of Liberty, where the building was designed entirely in steel with all connections being bolted, (Koklanos, 2011) to allow for demountability. Uy et al. (2017) has recently outlined research carried out to develop steel and composite demountable structures. This research considered beam-beam, column-column and beam-slab connections to promote demountability. Detailed experimental studies of these types of connections have been carried out by Li et al. (2016a,b and 2017).

3.3 Rehabilitation

Rehabilitation of steel and composite infrastructure is most frequently encountered in bridges. This has had significant interest over many decades in other parts of the world and will continue to be an increasing problem with the coupled effects of ageing infrastructure and ever increasing loads due to increased productivity, (Khan, 2012). Furthermore, offshore structures also pose a particularly unique example of a steel structure where extreme loads can often require rehabilitation and there is also an increasing need now to look at the decommissioning of offshore steel structures, with the steel production platforms and the support structure, providing a major source of potential reusable steel for the world in future, (Reddy and Swamidas, 2013). Demountable and rehabilitated steel and composite infrastructure are definitely of interest in the future

4. STRUCTURAL HEALTH MONITORING

Structural health monitoring has been mainly used on iconic structures in the past, for example Tsing Ma Bridge, Hong Kong, (Chan et al. 2011, Li et al, 2011 and Li et al, 2012); Guangzhou TV Tower (Ni et al, 2009, Chen et al, 2011 and Yi et al, 2012) and more recently on the Sydney Harbour Bridge, (Nguyen et al. 2014). These systems however are now becoming more pervasive, particularly in regions where there is significant built infrastructure development, (Ou and Li 2010 and Uy et al. 2009). The Lotte Tower in Seoul, Korea also has a structural health monitoring system which is linked to the Building Information Model, Kim et al. (2015). Structural health monitoring techniques using contact and non-contact technologies able to be utilised for structures other than iconic structures will lead to more efficient maintenance of infrastructure in general.

5. STRUCTURAL RELIABILITY

Structural reliability approaches in the past have focussed on the issues of loads and capacities from fairly specific sources. For example, on the loading side, wind loads and earthquake loads have been characterised by historical records. These records are updated based on data which is quite regional in nature. Furthermore, on the capacity side structural materials, such as steel have been characterised based on an element being used on a project which has inherent properties from known manufacturers. On the loading side, structural health monitoring now provides the ability for model updating, whereby the results of structural health monitoring systems can be used in real-time to assess loads far more accurately, (Frangopol, 2010 and Orcesis & Frangopol, 2010). On the capacity side however, with the potential increased uptake of steel reuse, elements are far more likely to have a higher coefficient of variation in their geometric and material properties and this will need to be reflected in design, (Fujita & Iwata, 2008b and Orton et al, 2012).

Structural reliability approaches to assess the capacity of structural sections considering new advanced steels and reused steel is therefore of considerable importance in the future. Furthermore, reliability approaches have in the past focused on structural elements and in the future structural reliability of systems will lead to improved efficiency and safety of structural systems, (Thai et al, 2016).

6. FURTHER RESEARCH & CONCLUSIONS

The challenges facing the world in future with regard to the $1 billion per annum Global Infrastructure Gap have been highlighted herein. Solutions to assist in reducing this gap have been highlighted in the context of future technologies in the area of steel and composite structures. This paper has then highlighted the key areas in these frontier technologies, namely

- Advanced Materials;
- Innovative Structural Systems;
- Structural Health Monitoring; and
- Structural Reliability

Whilst these areas of relatively independent it is argued that in the future, for our infrastructure to become more efficient, these areas need to be more intertwined. Thus, structural systems need to be chosen employing advanced materials, which allow for the concepts of structural health monitoring (SHM) to be implemented. Using the real time data from SHM techniques, reliability approaches can be employed to calculate real time capacities and remaining life of our infrastructure. These concepts if brought to bear can then assist to inform infrastructure owners to prioritise repair and to also enable revision of remaining life of structures. These synergistic principles, whilst appearing simple and obvious can have an enormous impact on the funds spent on our world's infrastructure in the future and our future quality of life.

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