CAHIERS MAGELLANES-NS
Volume 06 Issue 1
2024

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
http://magellanes.com/

ADVANCED ANALYSIS OF STEEL-CONCRETE COMPOSITE STRUCTURES - AN OVERVIEW

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ABSTRACT

The main purpose of this study is to establish a framework for advanced analysis of composite frames of steel concrete by establishing basic models for CFST columns, composite beams and composite connections. This study focuses primarily on circular CFST columns, composite beams with headed shear clamps welded via profiled steel sheeting, & CFST columns with a composite beam that uses blind bolted endplate connections, such as CFST columns, composite beams and composite connections. In this paper, the experimental and numerical examinations of such members are examined (finite element models). This study provides an overview of prior and recent research on the inelastic secondary analysis of structures (advanced analysis). Finally, the literature assessment highlights potential study gaps and briefly discusses the necessity of addressing these research gaps.

Keywords: Composite Structures, CFST columns, Composite Beams, Composite Connections, Profiled Deck Slab, Blind Bolted End Plate Connection

INTRODUCTION

Composite frames of steel concrete are widely employed in today's construction sector. This is due to the structural and monetary advantages offered by composite technology. Concrete is the commonly used material for construction because of many reasons, such as its high compressive strength, solid fire resistance, long life, ease of casting in any form or size and inexpensive cost. The quality of concrete, such as strength, setting time, resistance to fire and workability may be improved by different types of cement and additives. Concrete's weaknesses include its low tensile strength and general cracking and crushing. Steel, on the other hand, is a highly tensile substance. But it is a costly material with a low resistance to fire. The combination of concrete and steel nonetheless benefits from its compressive strength and its tensile capacity, as well as other structural and economic benefits from its ensuing composite elements, such as CFST columns and composite beams. This study jots down the important parameters to understand the behaviour and analysis of composite frames of steel and concrete. This study focuses primarily on circular CFST columns, composite beams with headed shear clamps welded via profiled steel sheeting, & CFST columns with a composite beam that uses blind bolted endplate connections.

CFST columns have many structural advantages, including high strength, superior ductility and a great capacity for energy absorption (Han et al., 2014). Concrete and steel benefits are integrated into CFST columns. Static and seismic performance with CFST columns are also outstanding (Wang et al., 2009). CFST columns are commonly employed in structures, such as buildings, bridges, towers, and substations because of these advantages. Composite concrete beams are often utilised in steel-framed construction (Faella et al., 2003; Gianluca Ranzi & Zona, 2007). Robinson's research on a comprehensive experimental analysis of composite steel beams with profiled steel sheeting started nearly fifty years ago (1969), which also carried out 17 composite beam tests, sums up the general

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
http://magellanes.com/

details of 58 previous experimental studies on composite beams with profiled steel sheets. Whereas, Ernst et al., 2010; Loh et al., 2004; Nie et al., 2004, 2008; G. Ranzi et al., 2009, they all conducted full-scale testing. The experimental data on such connections with composite slabs examines changes in the behaviour of connections with and without slabs (Katwal et al., 2017; Loh et al., 2006; Mirza & Uy, 2011).

CONCRETE-FILLED STEEL TUBULAR COLUMNS

Due to several structural and economic benefits, composite steel buildings consisting of CFST columns are often used in modern construction (Han et al., 2014; Katwal et al., 2018; Liew et al., 2014). The main constructive advantages of CFST columns are their high strength-to-weight, fire resistance, ductility and important capacity for energy absorption (Deng et al., 2017; Han et al., 2014). In addition, shuttering while construction is not necessary to save both money and time (Han et al., 2014). In addition, CFST columns offer excellent seismic performance (Wang et al., 2009).

The CFST columns are widely employed in buildings, bridges, towers, electric transmission lines and substations as major compressive elements (Han et al., 2014). CFST columns with different cross-sections such as circular, square, and rectangular can be used. For aesthetic and architectural purpose CFST columns with polygonal and elliptical cross-sections are used. CFST columns are now being explored using different cross-sectional shapes, such as octagonal CFST columns (Luo et al., 2012). Likewise, (Liew et al., 2014) studies were performed with double-skin tubular CFST columns.

High-strength steel and concrete materials have been rapidly developed and used in structures in recent years. With such strong materials, the cross-section dimension of CFST columns can be lowered, allowing more valuable space to be employed. CFST columns are included in Latitude Tower (222 m high) in Sydney, Australia; Two-Union building (226 m high), USA; SEG Plaza (356 m high) in Shenzhen, China; Taipei 101 Tower (508m high) in Taiwan (Liew et al., 2014). These examples show the development and application in CFST columns of high-strength steel and concrete as well as the growing popularity of such columns in the construction industry. Figure 1 is a typical composite frame construction photo with circular CFST columns.

Figure 1: CFST composite frames (Wang et al., 2009)

Experimental studies of CFST columns

CFST-column experiments began in the 1960s and have continued since then (Katwal et al., 2017;

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
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Wang et al., 2009) (Wang et al., 2009). Goode (2008) collected 1819 column test data covering CFST Circular and Rectangular (mainly square) columns. Goode's latest study (2008) revised (Xiong et al. 2017) to incorporate 2069 test results, of which 36 were UHSC-focused and high strength steel. However, most of the testing was conducted on standard strength concrete and steel. Roughly 71.9 per cent of CFST columns were tested on f_c' fewer than 50 MPa, 18.8 per cent on f_c' between 50 and 90 MPa and 9.3 per cent on f_c' between 90 MPa and 243 MPa. In steel, 91 per cent of CFST column tests were conducted for f_y under 460 MPa, 4.2 per cent were conducted for f_y between 460 and 550 MPa and the remaining tests were conducted at f_y between 550 and 853 MPa (Xiong et al., 2017). The circular CFST column generally gives the strongest confinement to the concrete core, hence greatly improving the strength and ductility of the concrete. Local buckling is more sensitive in square or rectangular CFST columns, however, these columns are increasingly used for aesthetic purposes and easy beam to column connection design and high cross-sectional bending rigidity (Han et al., 2014). To calculate the column strength, a database of 2194 CFST columns was used (Katwal et al. 2018). Most of the results indicate only the ultimate strength, which is troublesome because the definitions of the ultimate strength of different authors' may differ (Katwal et al., 2017). Consequently (Katwal, et al., 2017), who created a database of 154 square, 142 circular, and 44 rectangular specimens, only make consistent comparisons of the test data with the identified full-range curves. To verify FE models and simplified numerical models, a database built (Katwal et al., 2017) with recently published test findings (Xiong et al. 2017) and a particular focus on materials with high strength can be employed.

Three-dimensional finite element modelling of CFST columns

The actual behaviour of the CFST columns may be known by analysing the shell and solid element modelling in three-dimensional (3D) finite element (FE) software. As full-range load against deformation curves may be achieved, it is possible to precisely forecast structural parameters such as initial rigidity, ultimate strength, and capacity deformation. 3D FE models are often used for simulating CFST columns (Hassan, 2016; Katwal et al., 2017; Wang et al., 2009). The underlying behaviour of CFST columns may be thoroughly explored using such extensive FE models. High-strength steel and concrete are developed quickly and used in CFST columns, so small tubes are more likely to be used in composite columns. The FE model needs to take the properties of different steel grades and concrete strength into account to give the right projections. In addition, the FE model should be able to reproduce passive containment of steel tubes.

Simplified numerical modelling of CFST columns

The detailed three-dimensional (3D) Finite Element (FE) models can be developed to adequately forecast the behaviour of composite structures, however, such models are time-consuming to build and inadequate for major structural or routine design studies. These problems are mostly caused by the complexity of the modelling and the difficulty of convergence and excessive calculation durations. Therefore, to overcome such difficulties, one can use the fibre beam models (FBE). They are simple in modelling and have excellent computational efficiency. They are also suitable for advanced composite frame investigations. The essential difficulty, however, is the construction of sufficient material models to take the interaction of the steel tube with the core concrete into account.

A few steel and concrete stress-strain models are available in the literature for the FBE modelling of circular CFST columns. (Ahmadi et al., 2017), (Ahmadi et al., 2017; Luo et al., 2012; Roverso, 2018; Sakino et al., 2004; Xing et al., 2016) offered empirical and experimental-based material models. The issue of using experimental data to create uniaxial material models is that contributions from steel and concrete are rarely accurately measured (Deng et al., 2017).

For steel, an elastic-plastic reaction with or without strain hardening is usual to practise. The concrete curve is then generated by eleminating the steel component from the experimental data. An empirical concrete model can then be developed using regression analysis. Although empirical models can

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
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provide acceptable predictions, the actual interaction between the steel tube and the core concrete cannot be fully reflected because the effects of local buckling and concrete containment have not been appropriately included in the steel model. In addition, the validity of empirical models is restricted to the test data range for optimising model parameters and the accuracy of empirical models depends on the input quality.

COMPOSITE BEAMS WITH PROFILED STEEL SHEETING

Steel beams with ribbed and curved steel sheets, known as "composite beams" are generally used in modern steel structured building. The concrete is typically poured in composite slab beams on thin and profiled steel sheeting, which is then attached to the steel I section beam by the welding of the headed stud shear to the top flange of the beam. For composite beams, the use of profiled steel sheeting offers an instant working platform and functions as a permanent formwork to eliminate the expensive removal of the formwork necessary in standard rectangular reinforced concrete structures. The profiled steel sheeting cell shape also helps in the installation of pipelines inside the floor, which helps in combining and distributing services within floor depth (Abdullah, 2004).

Experimental studies of composite beams

Comprehensive testing of composite beams is complicated, time-consuming and needs significant test facilities, thus expensive (G. Ranzi et al., 2009). Robinson (1969) and Grant et al. contributed to the experimental research of composite beams with profiled steel sheeting that began over 50 years ago (1977). Grant et al. (1977) created a database of 58 composite beams (4572 mm to 11125 mm length) tested between 1964 and 1977. Grant et al. (1977) recommended further research since there were numerous uncontrolled and unknown factors in the earlier test findings. Grant et al. (1977) carried out 17 experiments on these composite beams, changing the yield stress of steel, deck shape and partial shear connection degree.

Grant et al. (1977) developed a composite beam design formulation that contained a reduction factor to calculate the capacity of the stud shear connectors in the rib of the composite beams for the stud connector strength in solid slabs. The requirements of the American code (ANSI/AISC 360-05) are based on this study, however, these standards are widely regarded as excessively broad (G. Ranzi et al., 2009). Further investigation has been conducted, including Easterling et al. (1993), Johnson and Yuan (1998), (Salvatore et al., 2005), (Braconi et al., 2015) and others to tackle the problem. In many cases, push tests were utilised to establish the behaviour of shear studs, but push testing indicated premature modes of failure. The use of such push tests to anticipate composite beams' behaviour must thus be questioned (G. Ranzi et al., 2009). According to the push tests results, shear stud behaviour revealed considerably decreased ductility than that of studies from composite beam testing (Bamaga, 2013) and Hicks and Smith (2014). Thus, the data extracted from full-scale composite beam testing are required to reach to a conclusion for better understanding of each and every element of composite beams.

Finite element modelling of composite beams

Detailed finite element (FE) modelling is a promising alternative technique to understand composite beams' underlying behaviour. FE modelling can be used to conduct thorough parametric evaluations because of prohibitively expensive experimental research on these composite beams. The complexity of the structure can however make it quite difficult to model the composite beams, in particular beam with profile steel sheets, to interact between different parts, non-linear materials and the inherently complex nonlinear behaviour of shear studs (Han et al., 2014).

FE models in push tests for composite beams and shear studs were studied (Ahmadi et al., 2017, Hassan, 2016, K et al., 2019; Lie et al., 2014; Nie et al., 2008; Of et al., 2000. Lam and El-Lobody, 2005; Tahmasebinia et al., Mirza et al.,2013, Nie et al., 2004; Queiroz et al., 2007; Ban et al., 2016. Cas et al., 2004). While implanting a stud in concrete, it is very difficult to understand the behaviour of the stud, making it next to impossible to capture the stud fracture. Therefore, a reduced model is necessary when

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
http://magellanes.com/

connector components are included to explain the interaction between the materials. For example, the model prepared by Ollagard et al. (1971) was the most widely used in the simulation of composite beams for researchers. The results of push tests with shear studs inserted in solid slabs were used to frame this model. The lack of a descending branch that shows the entire range of shear stud relationships is a fault in this model, and this can be remedied only if the effects of a concrete failure and shear stud failure are fully understood and taken into account in the model. Shear stud studies in push tests may not be typical of the studies of that in composite beams (Jayas and Hosain, 1989; Hicks, 2007). A comparison of test results for composite beams and those for accompanying push studies showed a lack of curvature and normal force due to floor landing (Hicks, 2009; Hicks, 2007; Hicks and Smith, 2014). In the composite beam testing, the shear studs are more ductile in nature than that derived from push tests. These behaviour differences are not taken into account in the model and other shear stud models show comparable disadvantages (Kwak and Hwang, 2010). Due to these limitations, FE models used to simulate shear studs are also limited in their capacity to predict the behaviour of the composite beams.

Simplified numerical modelling of composite beams

The preferred approach for routine design work and global structural analysis is simplified numerical modelling for composite beams. However, the thorough validation is required for these simplified numerical models. The complex orthotropic geometry of steel sheeting accounts to modelling problems with reduced methods for composite beams with profiled steel sheets; therefore the focus of this study is on simplified simulation methods which are already available.

Wright (1990) has developed a one-pitch composite floor system that separates the system's bending and shear motions. The tension zone was supposed to have failed and during the study only the remaining concrete was taken into account in the compression zone. At medium height of the un-cracked concrete, the concrete in the compression area was modelled like a thin plate. To connect the concrete panel with a profiled sheet of steel to transfer shear between cement and steel, dummy shear elements have been used. In the case of positive bending specimens, the specific crack under the neutral axis is valid, but this assumption cannot still apply to negative bending specimens or continuous beams when the concrete divides on the upper surface. Furthermore, because multiple dummy shear elements are needed to connect the concrete and profiled steel sheeting, the analysis of the composite beam is relatively difficult.

(Ahmadi et al., 2017) developed a non-linear FE approach to predict the structural behaviour of reinforced concrete slabs during fire. Yu et al. (2008) extended the study to see their behaviour by simulating composite slabs in fire environments. The top and lower ribbed portion of the profile each had a solid slab element and an equivalent beam element. Mindlin-Reissner (thick plate) hypothesis which states that each layer might have distinct temperature and material properties (Yu et al., 2008), was used to represent the slabs with nine-nodded layer plate elements. The mid-plane of the slab element's reference axis was considered to be the same as the beam element's reference axis. It produces an equivalent width in the cross section of this beam element based on the cross-sectional dimensions of the ribbed plate, and shares three central nodes on the solid slab element plane at the reference. The beam element represents a group of composite slab ribs and beam width instead of defining a number of strips.

The width derived from the rib width ratio is equivalent to the element (RWR). Because of the limited length of a single beam element used to describe the group behaviour of the profiled ribs, the shear stud beam interaction cannot be characterised by the correct shear stud, despite its simple model development.

CFST COLUMN CONNECTION

The place where the steel beams are connected to the CFST column is called the CFST Column Connection. Eurocode 3 (2005) calls them rigid, semi-rigid or pinned based on their initial rigidity.

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
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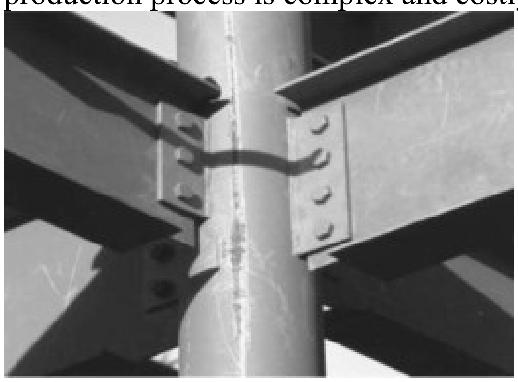
Some of the way that steel beams are connected to CFST columns are welded connections, through plate connections and fin plate connections. The steel beam ends of the CFST column can be welded, but the tensile and shear pressures are transferred directly into the steel tube. This could separate the steel tube from the central concrete and stress it over, in particular, for thin wall tubes (Hassan, 2016). Complex welded connections, like those disclosed by (Xing et al., 2016) with an external and inner diaphragm, are used to minimise rotating and enhance the rigidity of connections; (Katwal et al., 2018). For instance, external diaphragms are used in CFST columns in CFST frames (Han et al., 2011).
The finishing plates consist of a fin plate welded to a steel tube and structural bolts fixed on a steel beam. This on-site connection form is easy to set up. Fin plate connections are less rigid than weld and tube wall rips are common (Kurobane et al., 2004). On the other hand, in through plate connections, a steel plate is slotted across the hollow part and is welded to the opposite faces when the plate is connected. These connections have the advantage that their load resistance to the cross part is significantly increased, which leads to better capacity than counterpart fin plate connections even if the production process is complex and costly (Voth and Packer, 2016).



a) Typical Fin Plate Connection

b) Typical Through plate Connection

Figure 2: Typical fin plate and through plate connections

Endplate connections are made by welding the steel platform at the end of a steel beam and connecting the plate with a CFST column by means of structural bolts (specific structural bolts from the outside of the tube). Connections to the endplate can be split into three kinds based on the endplate length: header end, extended and flush.
If the measurement of the endplate is not as much of as the depth of the steel beam it is said to be a header endplate connection, whereas, if the length of endplate is larger than the height of steel beam it is termed as an extended endplate connection. And if the endplate’s length matches to that of the depth

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
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of steel is it a flush endplate connection. The flush plate is stronger than the header endplate connections, but has a lower capacity than the extended endplate connection (Hassan, 2016).

Experimental studies of CFST column connections

Because it is easy and efficient in production and assembly, CFST columns to composite beams with blind-bolted endplate connections are a feasible choice for multi-story building (Thai et al., 2017). Tao et al. (2017) have noticed that the initial stiffness and bending resistance have been significantly enhanced in the presence of a composite slab in their experimental research on CFST column connections. Thus the outcome here focuses on the CFST column with composite slabs using blind-bolted endplate connections.

The literature has several test sets for steel column sections with composite connections, such as those of Anderson and Najafi (1994), Xiao et al. (1994), Li et al. (1996b), Liew et al. (2000), and da Silva et al. (2001). However, there are still inadequate test data for study into CFST columns connections with composite slabs using blind bolted endplate connections as reported by Loh etal. (2006), Mirza and Uy (2011), Thai et al. (2017), and Tao et al (2017a).

A unique technique used by Loh et al. (2006) which engages five experiments on CFST column connections where blind bolted endplates wer bolted to hollow concrete columns. The percentage of reinforcement of studs as well as their spacing was investigated. The ductility of partial shear-connected composite joints were enhanced. In the meantime, higher ultimate moment capacity was achieved by increasing the reinforcing. A favourable reinforcement percentage of 1.0 to 1.5 percent was observed.

Mirza and Uy (2011) assessed the performance of the two composite connections, one under static and the other under dynamic load. Although both specimens had a similar behaviour, the ultimate capacity for static loading was on a higher note. Thus showing that composite connection behaviour was influenced by loading type.

Thai et al. (2017) investigated four blind bolted endplate connections, representing the interior composite region in experimental study. Effects of numerous CFST column forms and different types of endplate (four bolt rows extended endplate and three bolt rows flush endplate) were investigated. All four specimens failed in a ductile way and were usually rotated considerably. The plate in the bolt row adjacent to the concrete plate was significantly deformed, yet the bolt ran from the concrete as far as feasible. The concrete splits began outside the column, and then extended to the dome, producing a cross split that extended the length of the dome. The composite connection with the circular CFST column at times was 13.5% and 18.3% more than with a square CFST column with equivalent section capacity. When comparing composite connections with flat end plates with compound connections with expanded end plates, the combinations with extended terminals improve moment resistance and initial stiffness by 15 percent and 22.6 percent respectively.

Tao et al. (2017a) conducted seven composite connection experiments. All impacts were examined on the connected area of a slab, binding bars, kind of column steel (carbon or stainless steel) and load type (monotonic or cyclic). The exterior deformation of the square stainless steel tube produced by the draw out force of the top row of blind bolts prevailed over the inadequacy of the specimen which was monotonously tested. Significant changes were identified in the composite laboratory specimens, such as early degradation, such as cross-beton fractures in the column. The continuous longitudinal reinforcement fractured at its full capacity.

With increased deflection, the load bearing capacity decreased and profile sheeting cracks were noticeable. The effect of binding bars had some benefits with respect to improving joint capacity, but only the varied steel tube materials had a minor influence. The stiffness of the composite connection was changed by cyclic stress.

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
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Simplified numerical modelling of CFST column connections

To analyse the composite frame behaviour, simpler numerical models need to be created for CFST column connections. The composites are predicted perfectly by detailed FE models such as those produced by Mirza and Uy (2011), Atei and Bradford (2013), Tizani et al. (2013) and Hassan (2016). These models may also be utilised for behavioural research but are difficult to create routines and to analyse frames. On the other hand, simpler models in the analysis of frames are computationally highly efficient.

Pinned or rigid connections may easily be recreated with different connection design softwares. However, for semi-rigid connections, one connector element can define either the predicted moment-rotation ratio with analytical models or many connector elements with a computed stiffness of each component like Kang et al (2014). There might be a convergence difficulty when many connection components are employed, which renders it difficult to analyse big frames. On the other hand, if the moment-rotation connection is recognised, the single connector element can only be used for frame analysis.

STEEL CONCRETE COMPOSITE FRAMES

CFST columns, composite beams and composite connections function extremely well mechanically. Therefore, these are widely used in construction. Below is the listings on experimental composite frame research and framework design methodologies.

Experimental studies of composite frames

The literature has only a few experimental research on composite frames. A summary of the composite frame with steel columns evaluated by Leon et al. (1990), Jarett and Grantham (1992), Grantham and Jarret (1993), Li et al. (1996a) and Dhanalakshmi et al. (2002) was presented by Wang and Li (2007). In an experimental investigation, Wang and Li (2007) also studied two-story steel-concrete composite frames using a steel column section. A flush end-plate connection at the tip of the beam is welded and bound to the flange of the column to establish the beam-column connection. A four-bay composite structure was evaluated by Guo et al. (2013) lacking an unsupported centre column, to understand the column loss and the resistance mechanism of progressive collapse of a composite frame. Han et al. evaluated composite frames in the square CFST columns with steel beams (2008). A total of six one-story frames were evaluated to understand more about their behaviours. Han et al. (2011) evaluated a one-story composite frame with a beam of steel, welded in six different ways to circular CFST columns. The two-bay frame with square CFST columns and steel beams was evaluated under a cyclic horizontal load by Wang et al. (2010). To date, only the composite frame samples examined by Nie et al. (2012) have composite beams to examine the impacts of composite action on composite frame compliance with CFST and composite slab. The test findings reveal that the use of a composite slab greatly boosts the rigidity, strength and energy dissipation capacities of such frames.

Literature review on advanced analysis of composite frames

The typical design method for structural frames is an (indirect) member-based design that has a history of more than a century and still is today. A design employing sophisticated analyses (direct technology) on the other hand is allowed only for steel structures in particular codes, such as AISC360-10(2010) and AS4100 (1998). The major focus of the past advanced analytical studies has been on bare steel frames such as Goto and Chen (1987), Ziemian et al. (1992), Liew et al. (1993), Kim and Chen (1999), Thai and Kim (2011), Zhang and Rasmussen (2013) and Thai et al. (2013). (2016). Some studies have been published on advanced analyses for composite steel-built frames with reinforced concrete columns (Liu et al., 2012), stainless steel (Salari and Spacone, 2001,) and concrete-built steel columns (Salari and spacone, 2001;). (Chiorean, 2013). Advanced analysis research is still in its infancy for frames with CFST columns and composite beams. The lack of experimental data for composite frames of this kind could be one reason for this. Second, the composite frames fundamental behaviour is still a mystery

ISSN:1624-1940
DOI 10.6084/m9.figshare.26312694
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(Nie et al., 2012). Although some efforts were being made to use the distributed plasticity approach for 2D frames with CFST columns (Hajjar et al., 1988; Hajjar and Molodan, 1988) or to use techniques such as the incremental-iterative arc-length technique for ultimate strength analysis of axial force and biaxial bending composite steel-concrete cross-sections (Chireon, 2010), there are still several attempts to do so.

Research Gap and scope of future research

While complete designs based on members can consistently predict the behaviour of the columns of CFST, these models are unfit for everyday design and framework analysis. The fundamental behaviour of composite beams consisting of profiled steel sheets is still unknown. Models of fibre beam elements (FBE) can contribute to a good combination of accuracy and simplicity, but the interaction between steel and concrete must be included by the material models. For the better understanding of the behaviours of the composite members 3D FE models are necessary. Several assumptions in FE models employed to facilitate the modelling of certain complex interactions, such as the interaction between shear stubs and concrete must be addressed accurately. The direct method for determining shear load strength as well as the axial force communicated by profiled steel sheets must be established. This arises the necessity of a universal 3D FE model with CFST columns, composite beams with profiled steel sheeting and their connections to understand the actual interaction properties of different materials and their behaviours. The currently available shear force slip models are based on push tests and the behaviour of shear studs gained by push strokes does not accurately reflect the behaviour of shear studs in composite beams. As a result, full-range shear force-slip curves may be constructed by careful FE modelling including failure.

CONCLUSION

Despite their extensive usage for modern construction, research on the advanced analysis of steel concrete composite frames utilising concrete-filled steel tubes is still in its infancy (CFST). Due to the computational efficiency, simpler numerical models are the best alternative for composite frame analysis. However, it is especially challenging to explain the composite movements between distinct components of a composite framework using simpler models. In particular, this work demands a precise knowledge of each component of the key composite frame behaviour. To build composite frames, a simpler technique based on sophisticated modelling is essential.

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