Structural Behaviour of Thin-Walled Composited-Filled Beams

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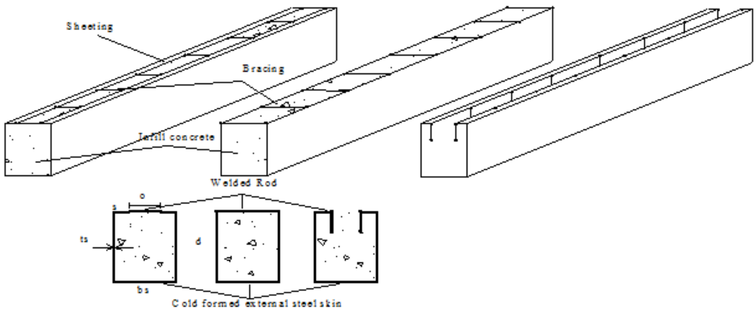
ABSTRACT
This paper presents a laboratory study to determine load and displacement relationship of the beams subjected 4-point loading, load and strain relationship of the beams, failure mode of the beams and to compare the experimental results and theoretical calculations. In this study, the number of specimens to be tested is 4. Field study would involve the experiment of the thin-walled composite-filled beams. The strength and failure modes of the beams are found to depend on the interface connections. The specimens were water cured for 7 days after removing them from the mould. Compressive and tensile strength tests were carried out on the specimens. Analytical models for the design of beams are developed and their performance is validated through experimental results using partial connection. The theoretical yield stress is 2667μm/m and these showed that the steel have yielded at ultimate loads. The ratio of experimental to theoretical values (derived from appropriate degree of restraint) ranges from 0.80 to 0.91, this shows reasonable agreement.

Key Words: Compressive strength, Tensile strength, beam, thin walled, buckling, strength, composite, cold-formed

INTRODUCTION
Thin-walled composite (TWC) sections are new ideas for beams. TWC sections comprising cold formed steel elements with an in-fill of concrete are suitable as replacement for hot-rolled steel or reinforced concrete in small to medium sized building. Typical TWC beams are shown in Figure 1 below.

Figure 1: Geometric of Composite Beams



The inherent advantages of this system are derived from its structural configurations. Open box sections for beams will allow easy casting of in-fill concrete. TWC sections do not require temporary formwork for in-fill concrete as the steel acts as formwork in the construction stage and as reinforcement in the service stage.

They are simple to fabricate and construct compared to conventional reinforced concrete where skilled workers are needed to cut and bent complex forms of formwork and reinforcement. The in-fill concrete is less likely to be affected by adverse temperature and winds as experienced in the case of reinforced concrete. The in-fill concrete is generally cured quickly and in any case, the load capacity of the steel alone may be relied upon for most construction loads. TWC sections are more susceptible to fire, although the thermal mass of the concrete in-fill provides reasonable protection to most fire loads. The smooth metallic finish of TWC sections is superior to conventional concrete and accepts more paint finish. Concrete filled steel elements as a means of providing aesthetic and economical structural elements attract interests in the construction industry.

The main objectives of this paper are to determine load and displacement relationship of the beams subjected 4-point loading, load and strain relationship of the beams, failure mode of the beams, and to compare the experimental results and theoretical calculations.

RESEARCH SIGNIFICANCE

Nowadays, the building of an elegant structure satisfying structural (strength associated with ductility and lightness), construction (feasible and simple) and economic (low cost) requirements are vital and the incorporation of thin-walled composite beams in building will be a step forward to meet those requirements. With this system, the steel strip is reasonably cheap to import and the cost of setting up a rolling mill is acceptable in quite poor countries.

The manufacturing of sheeting locally will aid the economy. However, the behaviour of thin walled composite-filled beams need to be and understood. When using this CSWR beam, the time required to finish the project will be reduced and become faster and easier. This is because we only need a thin walled steel and concrete to build a CSWR filled beam instead of using formwork and reinforcing bar to build the reinforce concrete beams.

EXPERIMENTAL STUDY

Comprehensive series of tests were conducted to study the behaviour of CSWR beams. The test specimens were fabricated with varying geometric, material and interface connection parameters. Thin-walled composite-filled beams consist of a cold-formed open steel box section with an infill concrete. Thin-walled composite beams (Figure 2) were classified, based on strength-enhancement devices, as Cold-Formed Sheet with Welded Rod (CSWR20), and Cold-Formed Sheet with Welded Rod (CSWR50). Experiments were conducted in 2 series: A and B. A brief detail of the experimental beams with geometric and material properties is presented in Table 1.

Theoretical Formula

Equation 1 is proposed for the determination of moment capacity, Mu (Hossain, 2003). For CSWR beams (without top and bottom longitudinal steel rods) without welded extension (y=0), use:

$$M_u = t_s f_{sy}\left(d^2 + db_s - 2N_s^2\right) - 0.425\gamma^2 N_c^2 b_s f'_c \quad \text{-----------------------------} \quad (1)$$

Description Of Composite Beams

The cold-formed steel box section used in this experimental is medium class. The dimensions of the specimen are 150mm depth (D), 150mm width (bs), 1100mm length (L) and 1.5mm thickness (to) shown in Figure 2.

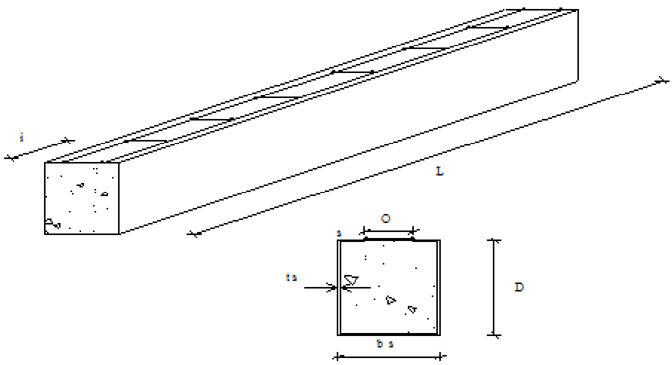
CSWR beams were provided with additional restraint with steel rods welded to the top of extension plate. The spacing of the welded rod is 110mm centre to centre and rods sizes that will be use are 2.0mm diameter, Ø.

Table 1: CSWR Beam Details

Beams Mark		Concrete		Cold-formed Steel Box Section				
		Type	f'c (MPa)	fsy (MPa)	Width, bs (mm)	Depth, D (mm)	Opening, o (mm)	Thickness, ts (mm)
CSWR20	A	NC	30	560	150	150	20	1.5
	B							
CSWR50	A	NC	30	560	150	150	50	1.5
	B							
L= 1100 mm, rod welded spacing, i = 110 mm and rod diameter ør= 2 mm								

*NC – Normal Concrete

Figure 2: Details of Typical CSWR Beams (Dimension details)



Casting for CSWR beams and Cubes

After the fresh concrete is produced, these fresh concrete will be poured into a six cube mould and four cold-formed steel boxes. The dimensions for each cold-formed steel box section are 150mm depth (D), 150mm width (bs) and 1100mm length (L). The specimens were cast horizontally and vertically with a natural sequence of their practical use in an especially fabricated stand. Care had been taken to avoid lateral buckling of thin steel plates especially for second series beams. Concrete was compacted in layers with portable poker vibrator. Control specimens in the form of cubes were cast to determine the concrete strength. After 24 hours of casting, the beams cured in water bath.

Before poured the fresh concrete into a cube moulds, make sure that all the joint edges and the surface of the cubes mould have been grease and all the bolts are tightened. Then put the cube mould into a vibrating table. Before switch on the vibrating table, pour the concrete only one third of the height of the cube mould. Then switch on the vibrating table until the concrete in the cube mould is absolutely compact. Then, after the concrete in the cube mould is absolutely compact, switch off the vibrating table and then poured again the fresh concrete until it reach another one third of the height of cube mould. Repeat the process until the concrete is full in cube mould.

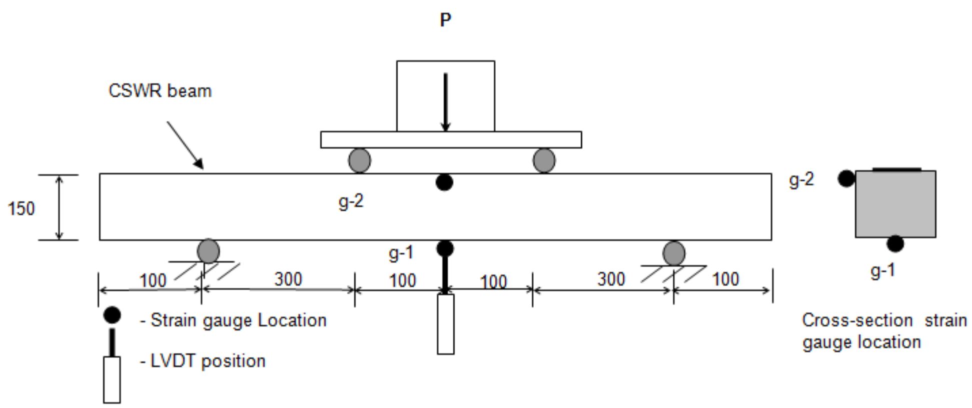
For the first series test, pour the concrete into a cold-formed steel box until it reach on third of the highest of the cold-formed steel box. For CSWR50, one rectangular plywood were put at the end left side of the beam and the other side are put as same the left side before cast the beams. Using the poker vibrator, vibrate the concrete in the cold-formed steel box until it absolutely compact. Repeat the procedure until the concrete is fully fill up the cold-formed steel box.

For the second series test, it is more complex to pour the concrete into the cold-formed steel box and these steps must be done properly to avoid any mistakes. The CSWR20 were concreted vertically because of the opening (20mm) is too small and the aggregate difficult to pass through in. Before pour the concrete into the cold-formed steel box, put the rectangular plywood plate at the both edge of the cold-formed steel box. In this situation, the rectangular plywood plate will be in the cold-formed steel box because the depth and width of the rectangular plywood plate are same as the inner depth and width of the cold-formed steel box. Then, the sell tape is used around the rectangular plywood plate to avoid any excess of the concrete from flow out. After all the processes are finished, pour the concrete one third of the length of the cold-formed steel box and vibrate the concrete using poker vibrator. Repeat the procedure until the last 10mm of the cold-formed steel box is left un-fill. To make sure that the last 10mm of the top of the cold-formed steel box is absolutely left un-fill, put another rectangular plywood plate on top of the cold-formed steel box. Stop filling the concrete when the rectangular plywood plate is same level with the end of the cold-formed steel box.

Instrumentation and Testing

The strain gauges were installed at mid-span of series A and B beams as shown in Figure 3. The strain gauge 1 was installed at the centre of the bottom plate while gauges 2 were installed on the side steel plate 15mm from the top and bottom. Typical test setup for beam tested under two point loading condition is presented in Figure 3. The specimens were tested in a hydraulic testing machine. The load was applied at increments and at each load increment strains and central deformations are recorded to get complete load-deformation and load-strain response. Central deflection was monitored by LVDT. The strains were recorded by using electronic strain measuring equipment. In preparing for CSWR filled beam samples to be tested, understanding on apparatus and measuring devices is necessary. Strain gauge, displacement transducer, load cells and data logger are among important measuring devices required in testing CSWR beam. The central point load was applied increasingly by using a testing machine, which consist of a test frame, hydraulic actuator and pump unit, a load cell, deflection control transducer and a control unit as shown in Figure 3 below:

Figure 3: Test Set-Up and Instrumentation of Composite Beams



RESULTS AND DISCUSSIONS

Failure Modes of the CSWR Beams

The first segment of the compression test is the observation obtained from the laboratory test. During loading process in Figure 4, the beam underwent flexural deflection (stage 1), followed by separation (stage 2) of side steel plates from concrete after initial cracking or debonding. The welded rod acted as mechanical interlock and anchored the top steel plate to the concrete. The lateral separation of sheeting from concrete in CSWR beams was delayed compared to another type of beams. With continued loading, concrete cracked at the interface of top rods (stage 3) causing interlocking force to deteriorate that initiated the lateral separation (stage 4) of steel at the top. At the same time, slip between steel and concrete (stage 4) was observed at the ends of the beam. As the lateral separation continued, the tag welds between rods and main steel skin (stage 5) started to fail. This enhanced the outward separation of steel and widened the gaps between rods and concrete core. Before the ultimate load, interface cracks propagated to the sides and deep insight into the concrete core.

At the failure stages, side steel plates buckled outward and took the cracked concrete with it. After the ultimate load, the steel skins buckled outwards diagonally (stage 6) at the loaded points, which was followed by local bearing at the supports and the loaded points (stage 7). The local bearing area of the steel was shown in Figure 4. Lateral separation of the plate started from ends of the beam and propagated towards the loaded point as shown in Figure 4.

The CSWR50 beams showed similar behaviour mode to that of CSWR20 beams although they had lower strength. Stages 5 and 7 of failure mode were absent in shallow (Sample A) CSWR50 beams with continuously welded rods. The welded braces restricted the outward buckling of the top steel plates and the failure was associated with outward buckling of steel skins and concrete cracking at the point of application of load at the centre. The pattern crack shown in Figure 5.

Load and Displacement Relationship

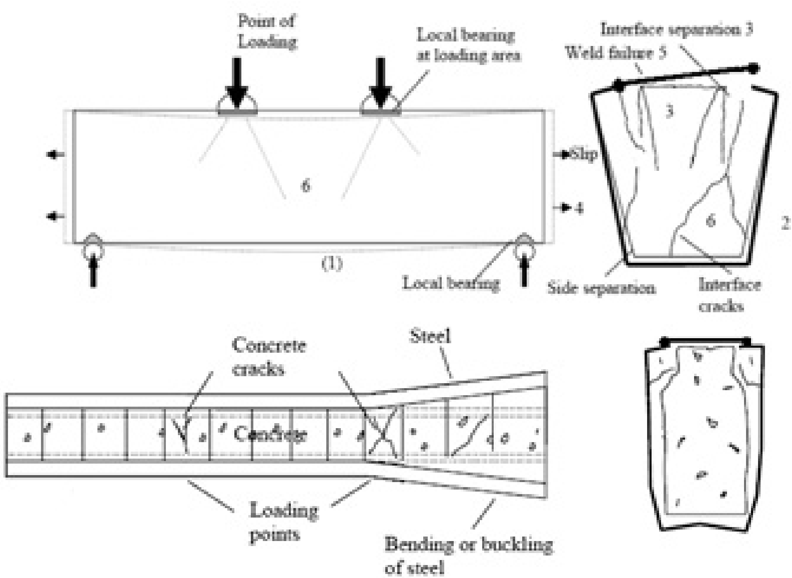
The ultimate strengths and vertical displacement are the elements that should be considered when collecting the data. The data from all the 4 samples of beam were taken and plotted.

From Figure 7, it is seen at the initial stage, the load increases almost linearly with displacement until about the yield point this indicates an elastic behaviour of the beam. Then, the displacement increase more rapidly. After the ultimate load, the load decreases with the increase of displacement. After this drop the load increases at a slower rate with a rapid increase of displacement. Another maximum load is reached before a sharp drop of load. The gentle plateau

shows a ductile behaviour.
The ultimate strength recorded on the sample A and B of CSWR20 was 144.7kN and 127.7kN at deflection of 7.67mm and 8.67mm respectively shown in Figure 5. The percentage difference between the higher value and the lower value of maximum strength which is from sample A and B is 11.75%. The percentage of the deflection differences is 11.53%.

The behaviour of CSWR50 beams was similar to CSWR20 beams. From Figure 6, the ultimate strength recorded on the sample A and B of CSWR50 was 125.1kN and 115.3kN at deflection of 6.49mm and 6.57mm respectively. The percentage difference between the higher value and the lower value of ultimate strength which is from sample A and B is 7.83%. Even though sample A and B have the different value of maximum strength, but the percentage of the defection between them is very small which is 1.22% if compared to the samples CSWR20.

Figure 4: Failure Mode of CSWR20



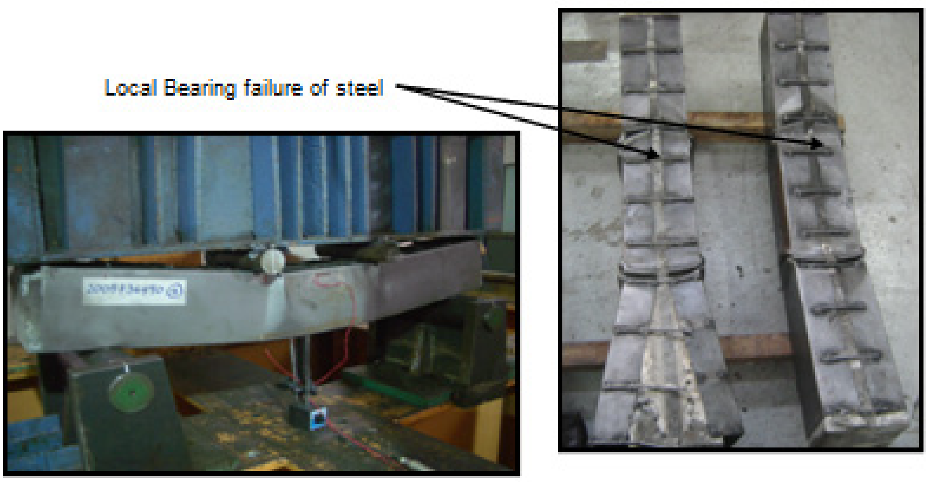


Figure 5: Failure Mode for CSWR50

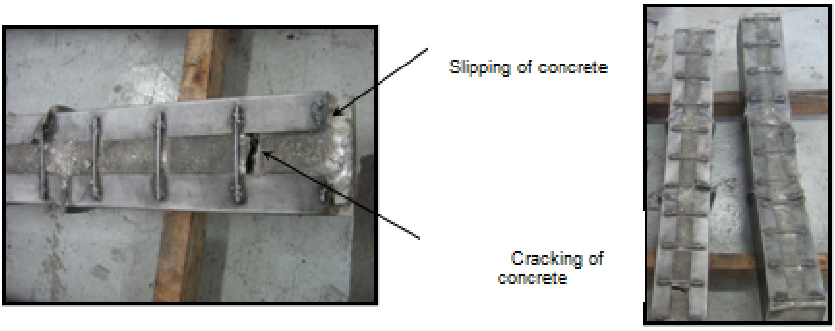
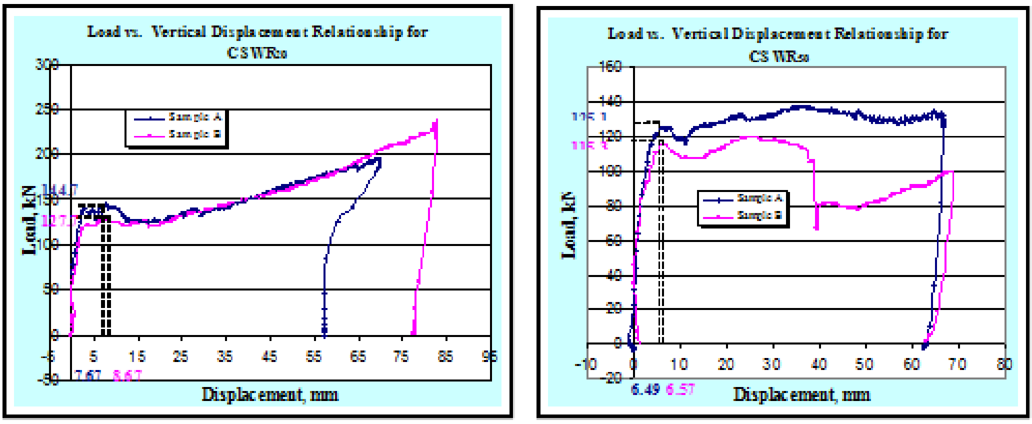


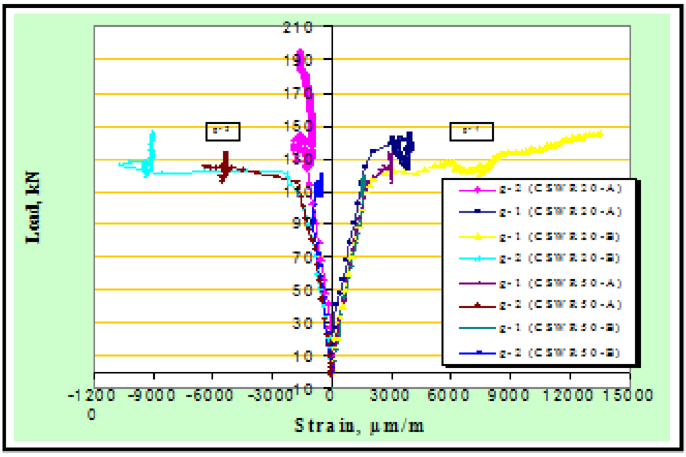
Figure 6: Load Against Vertical Relationship for Specimens CSWR20 andCSWR50



Load and Strain Relationship

Figure 7 shows the relationship between loads against strain for CSWR20 specimen and CSWR50. The maximum load recorded for both specimens A and B of CSWR20 are 141.4kN and 127.7kN respectively as shown in Figure 6. Meanwhile, the corresponding maximum strains for specimen CSWR20-A are 3107μm/m (g-1) and -1044μm/m (g-2) respectively and for specimen CSWR20-B are 8032μm/m (g-1) and -9089μm/m (g-2) respectively shown in Figure 7. The theoretical yield stress is 2.667x10-3 or 2667μm/m. these showed that the steel have yielded at ultimate loads. Figure 6 shows the maximum load for both specimens CSWR50 A and B are 125.1kN and 115.3kN respectively. Meanwhile, the corresponding maximum strains for specimen CSWR50-A are 2965μm/m (g-1) and -6337μm/m (g-2) respectively and for specimen CSWR50-B the strain are 1643μm/m (g-1) and -822μm/m (g-2) respectively.

Figure 7: Load Against Strain for Specimens CSWR20 and CSWR50



Comparison between Experiment and Theoretical Results

Table 2 gives the comparison result between experimental and theoretical. The ratio of Pexp/Pu for CSWR20¬¬¬-A is 0.91 (90.99%), CSWR20¬¬¬-B is 0.82 (82.20%), CSWR50¬¬¬-A is 0.86 (86.66%), and for CSWR50-B is 0.80 (79.87%). In theory, the values of CSWR ultimate load, Pu is bigger than the experimental, Pexp. The average of experimental ultimate load for CSWR20 is 144.7kN and for CSWR50 is 120.2kN. It can be concluded that CSWR50 are more practical and that a smaller opening gives more strength. The ratio of experimental to theoretical values (derived from appropriate degree of restraint) ranges from 0.80 to 0.91, this shows reasonable agreement.

Table 2: Comparison of Experimental and Theoretical Analysis

Beam	Theoretical Load, Pu	Theoretical Moment, Mu	Experimental Load, Pexp	Experimental Moment, Mexp	Pexp/Pu
	(kN)	(kNm)	(kN)	(kNm)	Mexp/Mu
CSWR20-A	155.41	23.31	144.7	21.21	0.91
CSWR20-B	155.41	23.31	127.7	19.16	0.82
CSWR50-A	144.43	21.66	125.1	18.77	0.87
CSWR50-B	144.43	21.66	115.3	17.30	0.80

CONCLUSIONS

From the experiment, it can be concluded that there are different value ultimate load, maximum vertical deflection and maximum strain for each specimens. Specimen CSWR20-A gives the highest value of the ultimate load and vertical deflection which are 144.7kN and 7.67mm respectively. By using results from the tensile test, the theoretical yield strain for the cold-form steel sheet is 2667µm/m. Both tensile (gauge g-1) and compressive (gauge g-2) strains in CSWR beam exceed the yield strain before ultimate load. This indicated that the analytical models for these beams could be developed, based on the yielding of the steel plate and supports the theory by Hossain (2004). The mode of failure for entire samples of CSWR20 beams is strength failure which is the samples crushed at the both ends of loading area, this behaviour also known as local buckling and local bearing failure respectively and side steel plates buckled outward and took the cracked concrete with it. After the ultimate load, the steel skins buckled outwards diagonally at the loaded points, which was followed by local bearing at the supports and the loaded point. The welded braces restricted the outward buckling of the top steel plates and the failure was associated with outward buckling of steel skins and concrete cracking at the point of application of load at the centre. The strength and ductility of CSWR20 beams are higher than CSWR50 suggesting feasibility of the design of such CSWR beam in practical circumstances. The ratio of experimental to theoretical values (derived from appropriate degree of restraint) ranges from 0.80 to 0.91, this shows reasonable agreement.

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NOTATIONS

bs, d, L	:	Width, depth and span of the beams respectively
o, s	:	Width of opening and top stripped steel respectively
ts , tse	:	Thickness of steel and welded extension plate respectively
Ast, Asc	:	Area of bottom and top steel rods respectively
v, Es	:	Poisson's ratio and Modulus of elasticity of steel respectively
Pexp,Mexp	:	Experimental ultimate load and moment capacity respectively
Pu, Mu	:	Theoretical ultimate load and moment capacity respectively
Σo	:	Cross-sectional perimeter of steel sheeting in contact with concrete
σb, kb	:	Buckling stress and bending buckling coefficient of steel plate respectively
f b, □	:	Shear bond stress at the interface and degree of edge restraint respectively
Nc,Ns	:	Neutral axis positions for concrete and steel section respectively
x	:	Distance from the support to the maximum moment