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Study of The Behavior of Composite Castellated Beam

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Abstract: Nowadays, steel construction has been widely used in structural construction. Steel has many advantages compared by the other material such as concrete or timber. Steel is more ductile and has more strength than the other material. One of the cross section which mostly used is castellated beam. Castellated beam is steel beam which has opening on its web. Some advantages of using this beam are increased the plastic moment capacity due to increasing of the beam's depth. In structural construction, castellated beam is usually combined with reinforced concrete slab called composite castellated beam. Therefore, aims of this study are to obtain and to compare the behavior of composite castellated beam and composite solid beam in frame structure. This research conducted experimental test and finite element modelling for validation. There are two types of frame structure considered. First, frame structure with composite castellated beam for the beam element and the second frame was composite solid beam as the beam element. The result showed that composite castellated beam had a better behavior compared by composite solid beam in terms of strength which are maximum load capacity, maximum peak displacement, yield load, yield displacement, structure stiffness, ductility, maximum moment, maximum rotation and energy dissipation.

Key words: Composite castellated beam, composite solid beam, energy dissipation, stiffness, yield load, maximum rotation

INTRODUCTION

Castellated beam is more popular nowadays. Several advantages of using this beam are increasing the bending capacity of the beam due to the increasing of the beam's depth (Frans *et al*., 2017a, b), reducing the total weight of the structure which corresponding to requiring less quantity of steel (Jamadar and Kumbhar, 2015) and passing underfloor service such as ducting and plumbing (Soltani *et al*., 2012). Besides the advantages of castellated beam, there are several disadvantages of castellated beam which are Vierendeel mechanism and local buckling sometimes took place caused by the stress concentration of the opening edges. Composite beam becomes one solution to prevent this collapse mechanism. On a simple beam structure, the composite beam has successfully applied to develop the plastic moment of the beam without local buckling or experiencing Vierendeel mechanism (Frans *et al*., 2017a, b). This condition caused by the beam will only sustain positive moment (top fiber will experience compression while the bottom fiber will experience tension) but the different things may be happened if the structure is a frame structure not a beam structure due to in frame structure, the beam member can be in positive moment or negative moment caused by the dynamic load such as wind load or earthquake load. Therefore, this research conducted experimental test and finite element analysis to obtain the behavior of composite beam on frame structure.

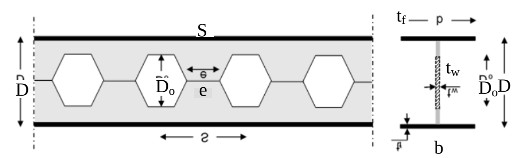

Fig. 1: Section properties of hexagonal castellated beam

Castellated beam: Castellated beams are fabricated by cutting and re-welding a hot rolled sections. Castellated beams are made by flame or laser cutting machine, along the x axis with a zig-zag pattern (Shendge and Shinde, 2015). There are many types of castellated beam such as hexagonal castellated beam, diamond castellated beam, circular castellated beam and many others. But hexagonal castellated beam is more chosen due to the simplicity of fabrication. Therefore, this research considered a hexagonal castellated beam as steel profiles to make a composite member.

Figure 1 shows the section properties of hexagonal castellated beam where D_o is opening depth, D is overall depth after castellation, t_w is web thickness, t_f is flange thickness, b is flange width, S is gross opening space, e is clearing opening space, α is opening angle.

Composite castellated beam: Composite castellated beam in this study is a castellated beam built with another different material which is reinforced concrete slab. The

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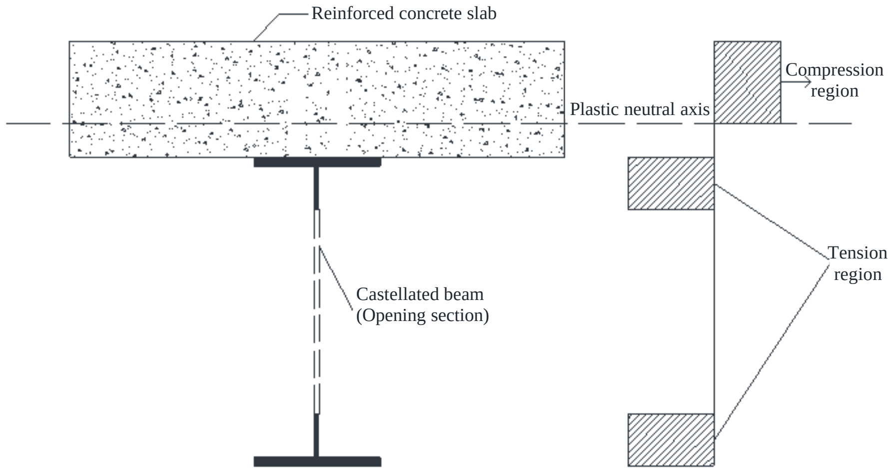

Fig. 2: Plastic stress distribution of composite castellated beam (opening section)

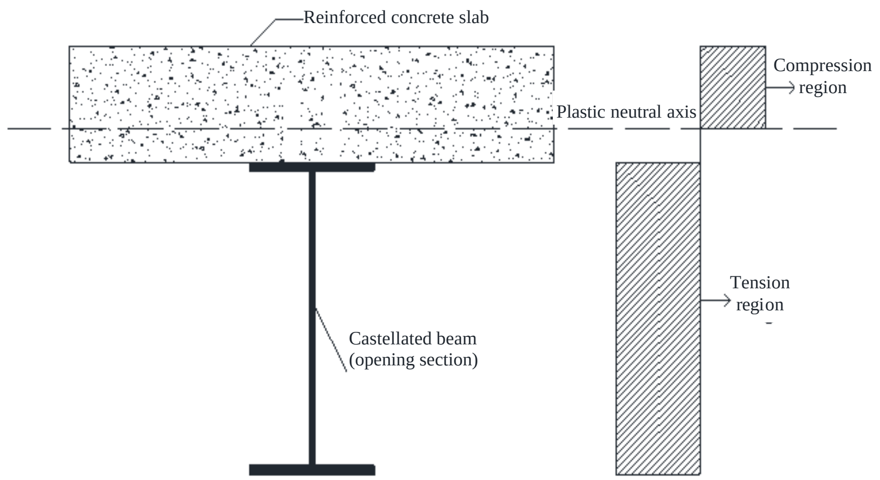

Fig. 3: Plastic stress distribution of composite castellated beam (solid section)

castellated beam and the reinforced concrete slab will work together against the external force. In composite structure. To develop the maximum strength of the beam study, one important factor must be noticed, that is the bond between the concrete and the steel profiles remain unbroken (Parung, 2017). Consequently, the shear connection must be well design. Once, the stud is well designed, the capacity of the beam will increase more significantly. This can be happened not only due to depth increasing of the steel profile after castellation (castellated beam) but also caused by the composite behavior between the castellated beam and reinforced concrete slab. Figure 2-4 show the plastic stress distribution of castellated beam (Frans *et al.*, 2017a, b).

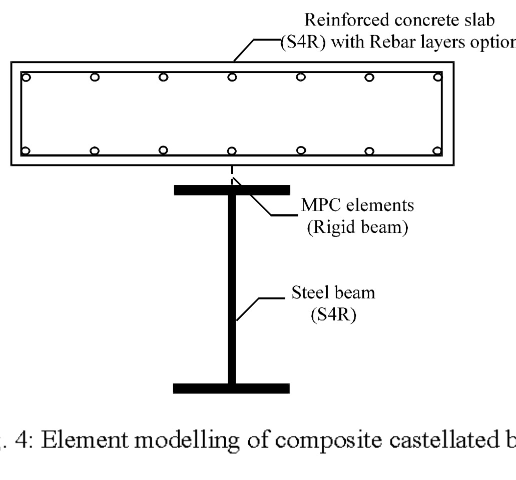

Fig. 4: Element modelling of composite castellated beam

Finite element analysis: In this research, finite element analysis was conducted using ABAQUS. Shell element with 4 nodes with reduced integration (S4R) was chosen for meshing purpose and the interaction between castellated beam and reinforced concrete slab used MPC Constraint option. This shell element and MPC Constraint option were chosen due to the robustness of strength prediction on beam structure. On the previous study, this element was success to predict the relationship between load and displacement on beam structure compared with the experimental test (Prakash *et al*, 2011). Figure 4 shows the element modelling of composite castellated beam on ABAQUS.

MATERIALS AND METHODS

To obtain the behavior of composite castellated beam on frame structure, this research conducted experimental test and finite element modelling which performed by ABAQUS. The frame structure which considered shown on Fig. 5 and 6. Figure 5 was structure frame with composite castellated beam as beam member while Fig. 6 was structure frame with composite solid beam as beam member.

Figure 7 and 8 show the study properties of the composite castellated beam and composite solid beam, respectively. This study properties of the castellated beam were obtained by using fast multi swarm optimization technique to achieve the optimum study properties (Frans *et al*., 2017a, b). To ensure there is no slip between the concrete slab and the steel profile, composite beam was designed based on fully composite theory using study's diameter of 16 mm. Cyclic loading (quasi-static) with displacement control has been applied at the peak of the column. The loading history was based on Steel-ATC-24 Protocol according to yield displacement obtained by monotonic loading (Krawinkler, 1992).

The material properties of the composite beam can be seen on Table 1. Figure 9 and 10 show the strain gauges and LVDTs location of each frame. Strain gauges were used to obtain the strain value of that location, due to assumption of the failure mechanism was yield of the entire study, the test was stopped if the strain value of the entire section considered reached the yield strain of steel which about 1130 μ. To ensure there is no buckling on the beam either local buckling or lateral torsional buckling, the LVDTs and strain gauges were placed to the location where the possibility of buckling occur. To satisfy the principle of "strong column, weak beam" and to prevent the yielding of the panel zone area, plastic moment of the column used was 2.69 times from the maximum plastic moment of the beam which was plastic moment of the

Fig. 5: Frame structure with composite castellated beam as beam element

Fig. 6: Frame structure with solid castellated beam as beam element

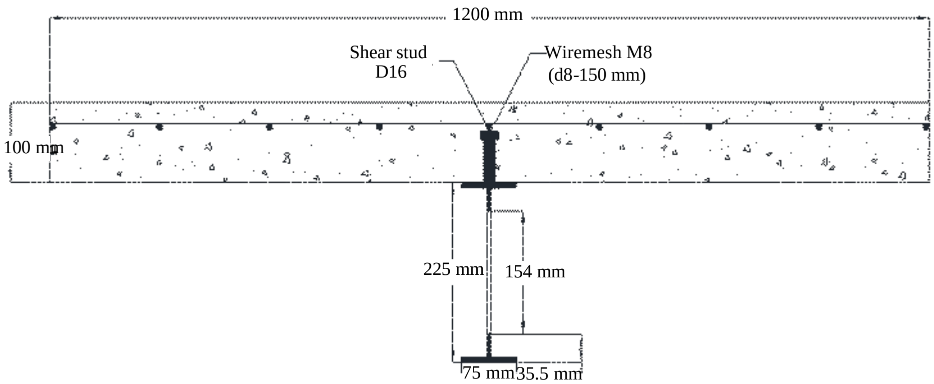

Fig. 7: Section properties of composite castellated beam

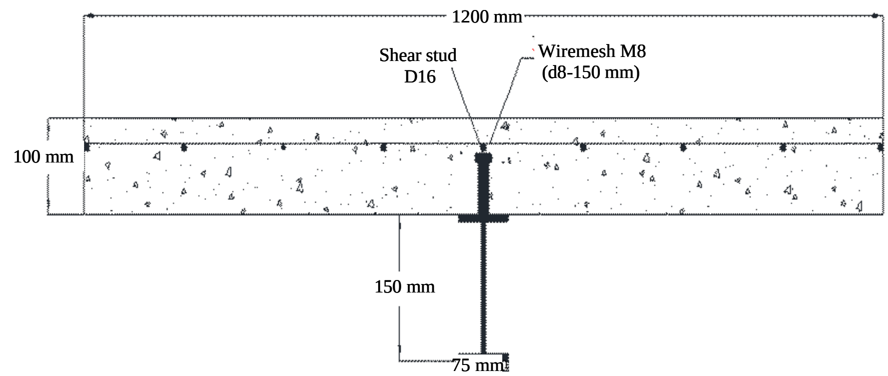

Fig. 8: Section properties of composite solid beam

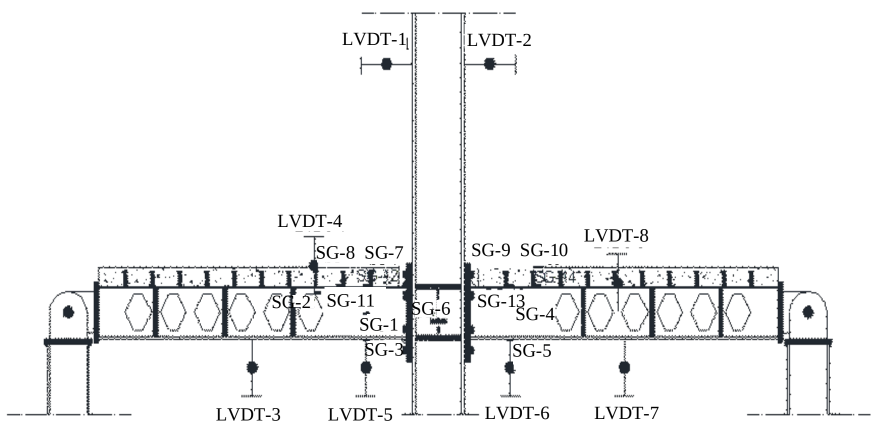

Fig. 9: Strain gauges and LVDTs location for the first frame structure (composite castellated beam)

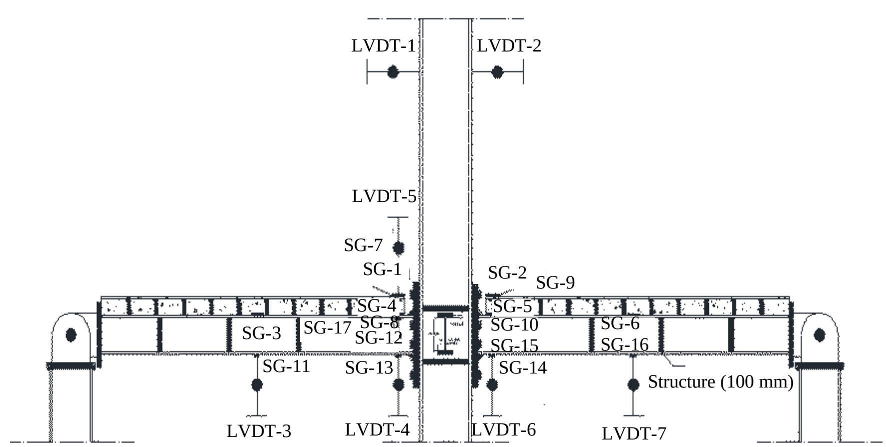

Fig. 10: Strain gauges and LVDTs location for the second frame structure (composite solid beam)

Table 1: Material properties of concrete and steel used

Material properties	Concrete	Steel
Density (kg/m^3)	2500	7850
Elastic modulus (MPa)	25310.27	216380.2
Poisson's ratio	0.2	0.3
Compressive strength (MPa)	29	-
Yield Strength (MPa)	-	243.89
Ultimate strength (MPa)	-	365.84

composite castellated beam, one strain gauge was located to the panel zone area of the column to monitor the strain zone. For obtaining the comparison between composite castellated beam and composite solid beam, there were 9 of the column due to high intensity stress on the panel variables considered such as maximum load capacity, maximum peak displacement, yield load, yield displacement, structural stiffness, ductility, maximum moment, maximum rotation and energy dissipation.

RESULT AND DISCUSSION

Structural characteristic: Figure 11 and 12 shows, respectively the relationship between load and displacement for first frame structure (composite castellated beam) and second frame structure (composite solid beam) obtained from experimental test and finite element analysis. Table 2 and 3 shows the comparison result between experimental test and finite element analysis. As it can be seen, the result of the experimental test and finite element analysis result were almost similar. Therefore, it can be concluded that the finite element analysis was accurately predict the behavior of both frame structure.

Based on Fig. 11 and 12, the behavior of each frame was obtained. There are 9 variables considered for determining the behavior of each frame structure. Table 4 shows the comparison of the behavior of first frame structure (composite castellated beam) and second frame structure (composite solid beam).

Based on Table 4, maximum load and maximum displacement which achieved of composite castellated beam (first frame structural) were higher 66.67 and 17.42%, respectively compared to composite solid beam (second frame structural) while yield load and yield displacement which obtained of composite castellated beam were higher 152.43 and 103.71%, respectively compared to composite solid beam.

There was an increase of the structural stiffness of the frame about 23.9% from composite solid beam to composite castellated beam. The maximum moment and maximum rotation which achieved of composite castellated beam were higher 74.73 and 19.14% respectively compared to composite solid beam. This met the requirement of special moment resisting frame according to SNI 1729:2002 (SNI., 2002). For energy dissipation, there was an increase about 95.99% from composite solid beam to composite castellated beam. But in the other hand, the ductility of composite solid beam was higher 42.36% compared to composite castellated beam. This may be caused by the test was stopped before the total collapse to prevent the frame structure fall down. If the test continued to the end, the maximum displacement might be higher than the maximum displacement achieved, hence, there will be an increase of the ductility of each frame and there is a chance that the ductility of the composite castellated beam higher than

Table 2: Comparison of experimental and finite element analysis from first frame structure

Variables	Experimental	Finite element analysis
Maximum load (kN)	50.28	45.60
Maximum displacement (mm)	119.00	111.19
Yield load (kN)	19.88	23.59
Yield displacement (mm)	39.52	47.49

Table 3: Comparison of experimental and finite element analysis from second frame structure

Variables	Experimental	Finite element analysis
Maximum load (kN)	28.78	27.36
Maximum displacement (mm)	93.44	94.69
Yield load (kN)	9.72	9.34
Yield displacement (mm)	24.73	23.31

Table 4: Comparison of experimental and finite element analysis from first frame structure

Structural characteristic	Composite castellated beam	Composite solid beam	Difference (%)
Maximum load (kN)	45.60	27.36	66.67
Maximum kisplacement (mm)	111.19	94.69	17.42
Yield load (kN)	23.59	9.34	152.43
Yield displacement (mm)	47.49	23.31	103.71
Stiffness (kN/mm)	0.50	0.40	23.90
Ductility	2.34	4.06	42.36
Maximum moment (kN-m)	75.42	43.16	74.73
Maximum rotation	0.04	0.03	19.14
Energy dissipation (kN-mm)	12831.42	6547.10	95.99

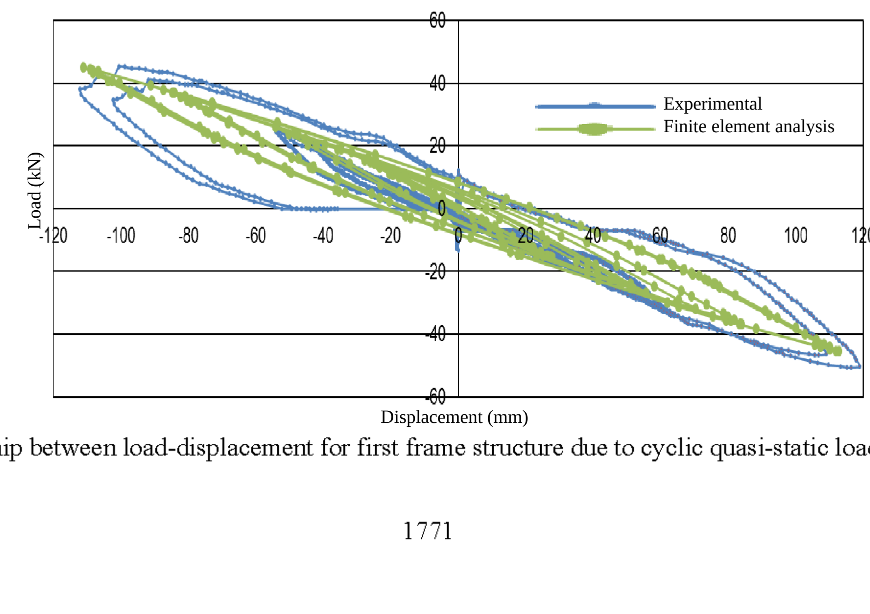

Fig. 11: Relationship between load-displacement for first frame structure due to cyclic quasi-static loading

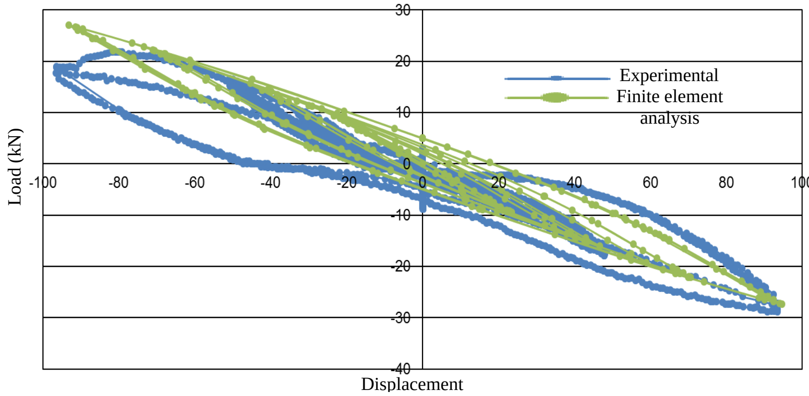

Fig. 12: Relationship between load-displacement for second frame structure due to cyclic quasi-static loading

the ductility of composite solid beam. As information, the stopping criteria of the test was yield mechanism which occurred on the entire section considered.

Failure mechanism: The failure mechanism of both structure was similar which was yield mechanism of the entire cross study considered. There is no local buckling on the web or flange of the steel beam. Vierendeel mechanism and lateral torsional buckling either local or global did not occur. The lateral torsional buckling did not occur due to considering the distance between each stiffener based on the theory which proposed by Kwani and Wijaya (2017). Besides, there is no yielding on panel zone, this is according to maximum strain recorded by the strain gauge which was only about 225.71 μ while the yield strain of steel used 1130 μ. It also can be noticed that the column still remains elastic during the test. Moreover, the endplate connection which were bolt connection to column and weld connection to beam have successfully developed the plastic moment of the beam with no prying action of the bolt and there was no fracture of the weld.

CONCLUSION

Experimental test and finite element analysis have been conducted to obtain the behavior of composite castellated beam and composite solid beam. There were two frame structure which have tested. First frame structure was frame structure with composite castellated beam as beam member and the second frame structure was frame structure with composite solid beam as beam member. The cyclic loading with displacement control used at the peak of the column. The Steel-ATC-24 protocol was used as the loading history. For finite element modelling, Shell element with 4 nodes Reduced integration (S4R) and MPC Constraint option were used. There were 8 variables considered to compare the behavior of composite castellated beam and composite solid beam. The result shows that behavior of composite castellated beam was better than composite solid beam. This can be seen from the significantly increasing of 7 variables which considered. The failure mechanism of composite castellated beam and composite solid beam was similar which yield occurred on the entire study considered with no local buckling and lateral torsional buckling either local or global on the beam member. The endplate connection has successfully developed the plastic moment of the beam either composite castellated beam and composite solid beam.

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