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Numerical Simulation and Parametric Study on the Moment Capacity of Composite Beam

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ABSTRACT

Response of structural components like beams have been studied by different methods. One of the methods which is widely used is experimental testing. But since it provides actual response, it can be quite costly and time consuming. However, finite element analysis has been used a lot due to capabilities of computer hardware and software. The use of software to model structural components is cost effective and much faster. In this study, ABAQUS was used for numerical simulation of a concrete filled steel tube (CFST) beam and the effect of width/thickness ratio, yield strength of steel tube, compressive strength of concrete and the stiffness on the moment capacity of the CFST beam were studied. The simulation shows good agreement with the experimental results. After validation of simulation, the parametric study on the moment strength of the beam was carried out to predict the simple equations for maximum moment capacity of CFST beam. It was observed that the capacity of the beam was governed by the steel tube strength.

1. Introduction

Composite members consisting of concrete filled steel tube (CFST) are widely used in high- rise buildings having very large moments, mainly in zones of high seismicity. Composite square

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concrete-filled hollow steel sections (HSS) have been used increasingly as beams, columns and beam-columns in both unbraced and braced frame structures. The CFST beams that consist of a steel section filled with concrete have several benefits over traditionally reinforced concrete (RC) beams. These beams have excellent moment carrying capacity, ductility and stiffness compared with the conventional steel reinforced members. This type of structure is better choice than steel members due to economical reason. By considering these advantages, steel section filled with concrete was opted for the study.

Response of structural components like beams have been studied by different methods. One of the methods which is widely used is experimental testing. But since it provides actual response, it can be very costly and time consuming. However, finite element analysis has been used enormously due to capabilities of computer hardware and software. The use of software to model structural components is cost effective and much faster.

In this study, ABAQUS will be used to simulate the load-deflection of CFST beams by considering geometrical nonlinearity. After validation of simulation results, the effect of different parameters (width/thickness ($\frac{B}{T}$), steel tube yield strength and concrete compressive strength) on the moment strength of the beam was carried out to predict the simple equations for maximum moment capacity of the composite beam.

2. Literature review

In general, concrete filling of steel tube is an effective procedure to avoid local buckling and to improve ductility of the hollow steel sections. CFST is one of the types of a composite structure that is providing a good result to the construction field by improving the strength and cost of the structure. Lin-Hai Han (2004) [1] presented a model to predict the behavior of CFST beams. A series of concrete filled rectangular and square tube beam tests were carried out for the prediction of load vs. mid-span deflection curves with the test results.

One concrete-filled steel beam (diameter-to-width ratio = 32) was tested by Furlong [2]. He observed that flexural strength of hollow steel tube was almost 49% lesser than that of the concrete filled steel beam. The conclusion presented by Furlong was based on only one specimen and cannot be generalized.

Later on, Prion and Boehme [3] tested four concrete-filled steel beams (with dia.-to-thickness d/t = 89.4), with high concrete strength (73 Mpa). Ductile failure mechanism was observed in these specimens. Lu and Kennedy [4] conducted tests on 12 composite beams. They observed the effects of different values of shear span to depth and different depth to width ratios. The results revealed that the maximum bending strength of the composite beams was improved by almost 10–30% than that of bare steel sections, depending upon the relative proportions of concrete and steel. The bending stiffness was also increased. Their main finding was the slip between the concrete and steel was not problematic.

Elchalakani et al. [5] showed an experimental study of the bending behavior of circular CFST beams subjected to large displacement. His conclusion was that thinner steel section strength, energy absorption and ductility improve with the void filling of the steel sections.

Hildemar Hernández et al .[6] studied the behavior of composite beams made of steel and concrete, (assembled by bolt-type connectors). Bashir et. Al. [7] presented the numerical simulation of composite structure and it was observed that the simulation of post-peak part of the experimental specimen cannot be done precisely by ignoring geometrical nonlinearity. There was lot of experimental data available on composite beam but simple equation to predict the bending capacity of composite beam was not available. The target of this research is to provide simple equation for the moment capacity of the composite beam after validating the numerical simulation of composite beam.

3. Numerical simulation

The CFST beam tested by Lin-Hai Han [1] will be simulated by using ABAQUS. Figure 1 shows the details of experimental specimen subjected to a point load. Specimen details are shown in Table 1.

Table 1.
Specimen details.

Specimen label	Sectional dimension $D \times B \times T$ (mm)	$\frac{B}{T}$	L (mm)	F_{cu} (Mpa)	F_y (Mpa)	E_S (Mpa)	E_c (Mpa)
CFST-1	$120 \times 120 \times 3.86$	31.088	1100	27.3	330	200000	26700

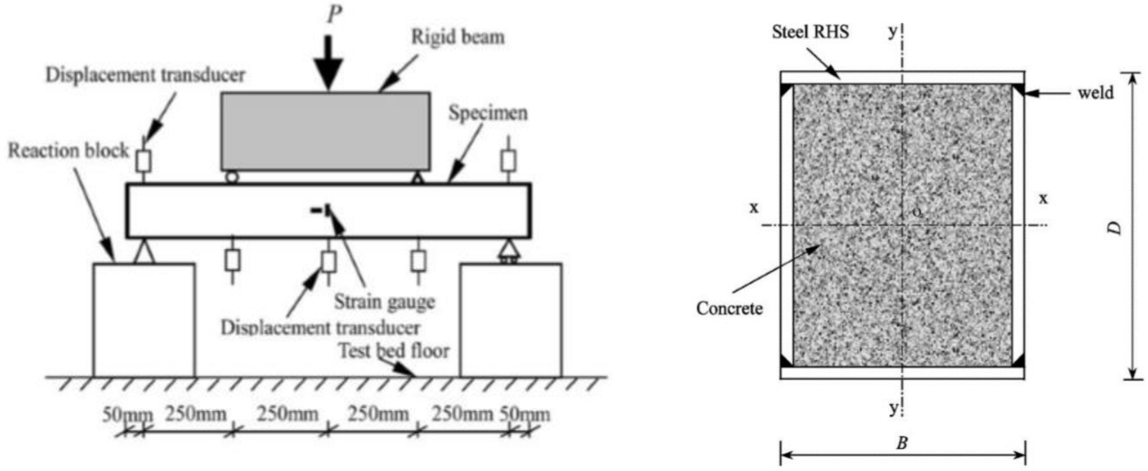

Fig. 1. Composite beam model dimensions and applied load [8].

3.1. Constitutive model

Material model for concrete in tension (Figure 2) presented by Belarbi and Hsu model for tension behavior of concrete [9] and compression stress strain model (Figure 3) of concrete developed by Todeschini model for compression behavior of concrete [4] were adopted in this study. Bilinear stress strain curve for the steel was adopted in numerical simulation of CFST beam as shown in (Figure 4).

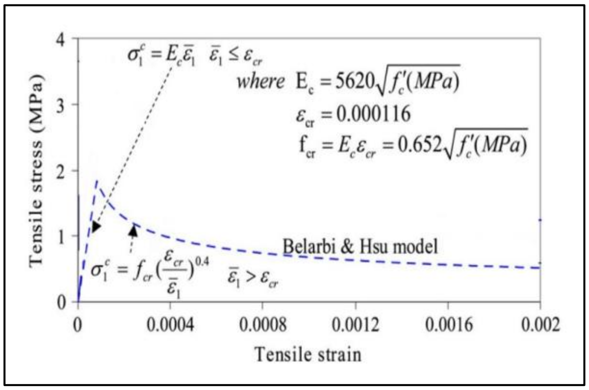

Fig. 2. Belarbi and Hsu model for tension behavior of concrete [9].

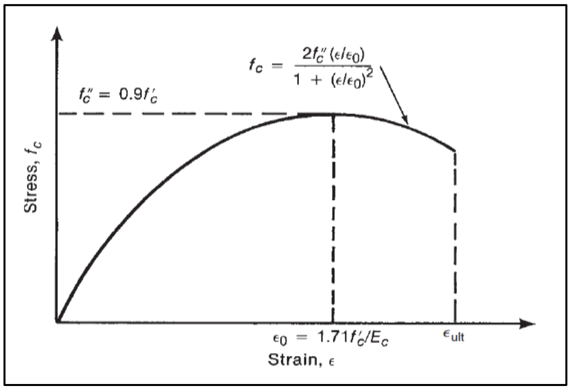

Fig. 3. Todeschini model for compression behavior of concrete [4].

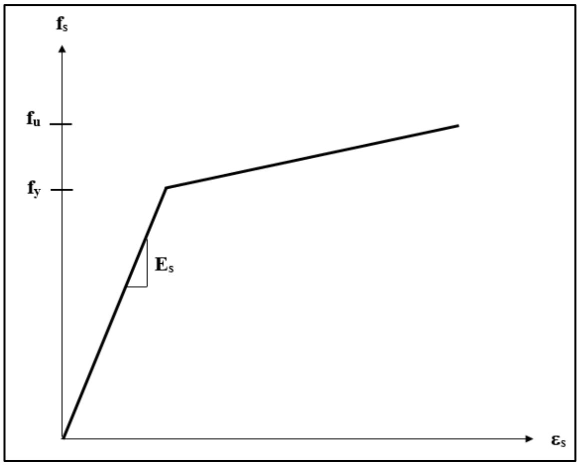

Fig. 4. Steel behavior.

3.2. Simulation of CFST beam

As a first step, simulation results of CFST beam are compared with the experimental results in terms of moment vs deflection curve as shown in Figure 5 and good agreement between the simulation and experimental results is observed.

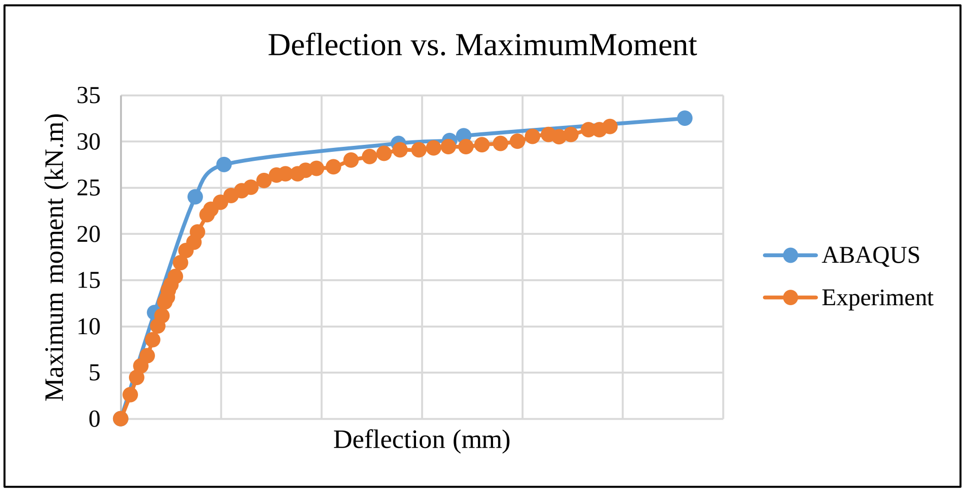

Fig. 5. Deflection vs maximum moment of specimen CFST-1.

Figure 6 shows the deflection of the beam specimen after the analysis, having large deflection at mid span.

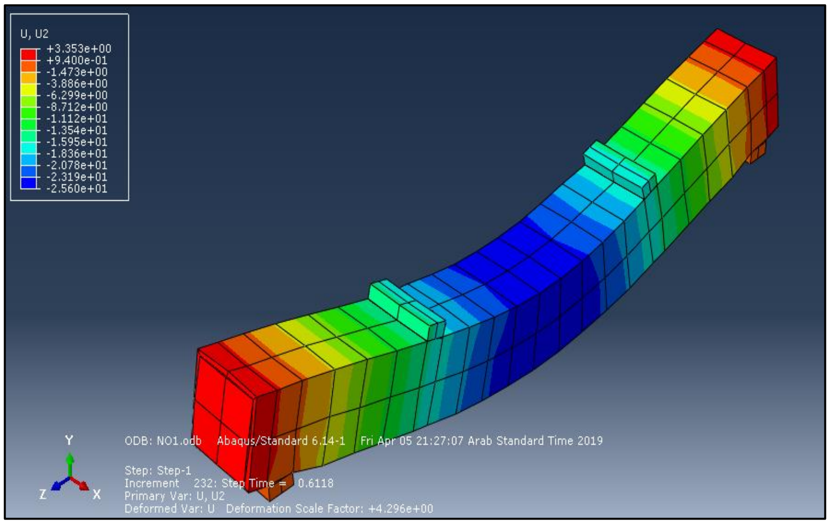

Fig. 6. Deflected shape of CFST beam.

3.3. Simulation of hollow steel beam

Studying the influence of concrete existence inside the steel tube:

In order to study the influence of concrete presence inside the steel tube, a hollow steel section beam has been simulated. Table 2 shows the details of a composite beam and a hollow steel section beam. Whereas, Figure 7 shows the moment vs deflection for the both cases. It can be perceived from the figure, that the moment and stiffness are reduced when we removed the concrete from inside the steel tube.

Table 2.
Specimen details of composite and hollow steel section (HSS) beam.

Number	Specimens label	Sectional dimension $D \times B \times T$ (mm)	$\frac{B}{T}$	E_S (Mpa)	E_c (Mpa)	F_{cu} (Mpa)	F_y (Mpa)
1	CFST-1	$120 \times 120 \times 3.86$	31.088	200000	26700	27.3	330
2	HSS	$120 \times 120 \times 3.86$	31.088	200000	-	-	330

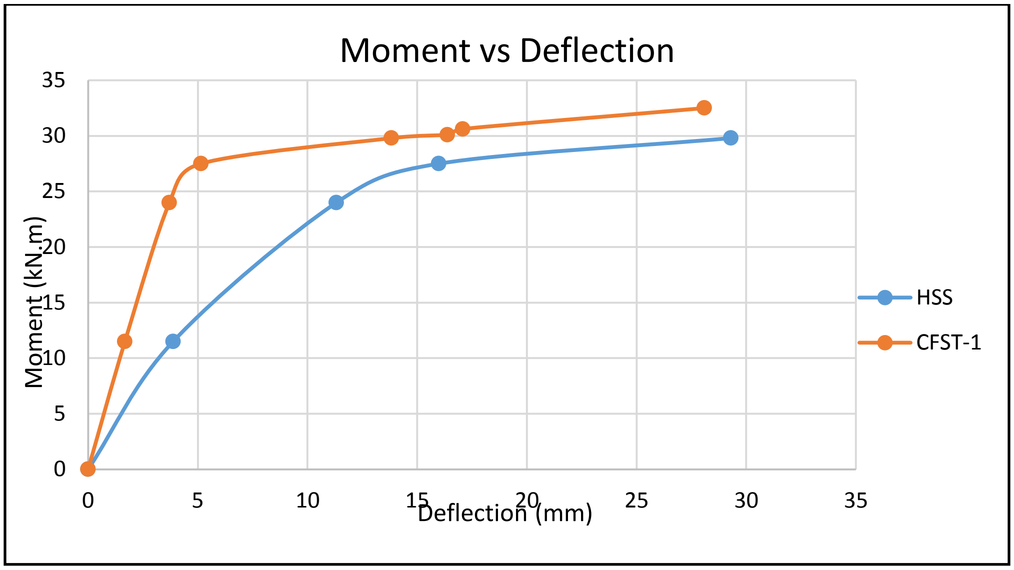

Fig. 7. Moment vs deflection of specimen CFST-1 and a hollow section steel (HSS) beam.

4. Parametric analysis of composite beam

After validation of simulation results, the effect of different parameters (width/thickness $\frac{B}{T}$), steel tube yield strength and concrete compressive strength) on moment strength of the beam was carried out to predict ultimate moment(yielding) capacity of the CFST beam.

4.1. Effect of B/T on the moment (yielding)

In order to observe the influence of $\frac{B}{T}$, three specimens with different $\frac{B}{T}$ ratios were analyzed by using ABAQUS. Specimen details of these specimens are presented in Table 3.

Table 3.
Details of specimens for different $\frac{B}{T}$ ratio.

Number	Specimens label	Sectional dimension $D \times B \times T$ (mm)	$\frac{B}{T}$	E_S (Mpa)	E_c (Mpa)	F_{cu} (Mpa)	F_y (Mpa)
1	CFST-2	$120 \times 120 \times 3.86$	31.088	200000	26700	27.3	330
2	CFST-3	$120 \times 120 \times 5.86$	20.47	200000	26700	27.3	330
3	CFST-4	$120 \times 120 \times 7.0$	17.14	200000	26700	27.3	330

The moment vs deflection curves for different $\frac{B}{T}$ is shown in (Figure 8).

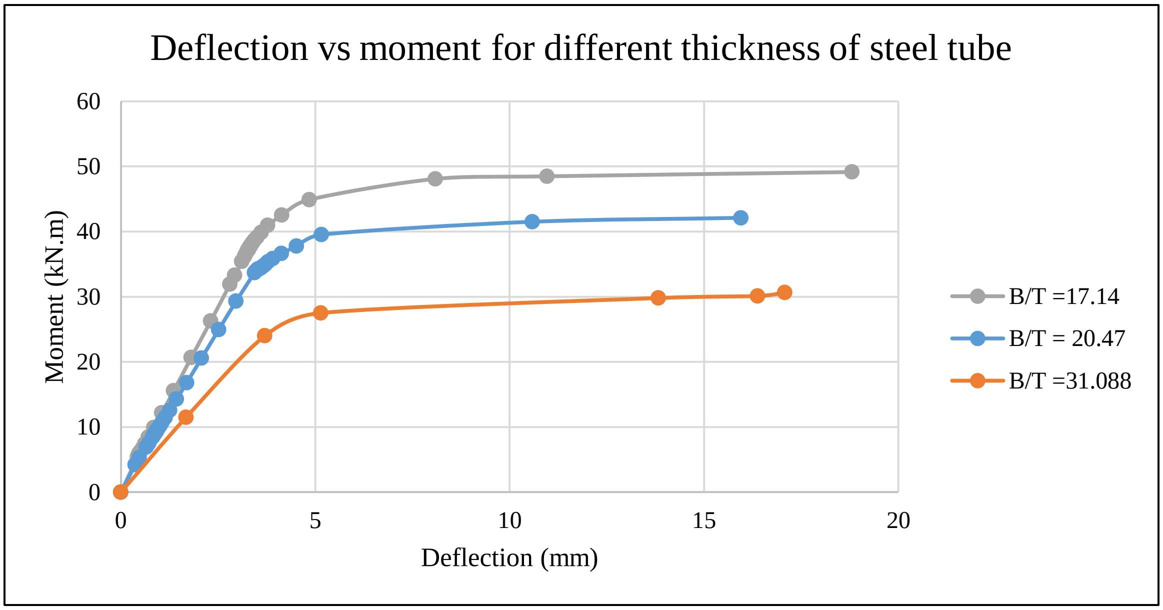

Fig. 8. Deflection vs moment at different $\boldsymbol{\frac{B}{T}}$ ratios.

By looking at Figure 8, it can be seen that with the increase of $\frac{B}{T}$ ratio, the maximum moment (yielding) reduces. In order to predict the moment (yielding) with changing the $\frac{B}{T}$ ratio, moment (yielding) vs $\frac{B}{T}$ ratio curve has been drawn as shown in (Figure 9).

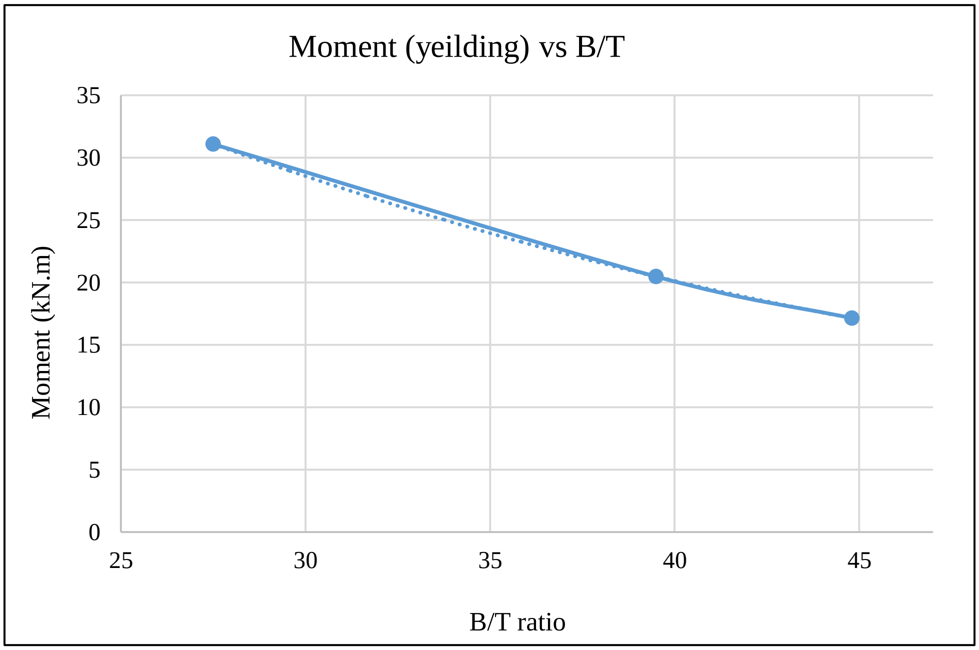

Fig. 9. Moment (yeilding) vs $\boldsymbol{\frac{B}{T}}$ ratio.

4.2. Effect of yield strength of steel on the moment (yielding)

Simulation of the composite beam at different yield strength of steel is done, to see the effect of yield strength on the moment(yielding). The details of specimens at different yield strength is shown inTable 4.

By looking at the moment vs deflection curve at different yield strength of steel in Figure 10, it can be seen that the moment increased with the increase of yield strength of steel. In order to predict the moment (yielding) at a given yield strength of steel, moment(yielding) vs yield strength of steel curve has been drawn (See Figure 11).

Table 4.
Details of specimens for different yield strength.

Number	Specimens label	Sectional dimension $D \times B \times T$ (mm)	$\frac{B}{T}$	E_S (Mpa)	E_c (Mpa)	F_{cu} (Mpa)	F_y (Mpa)
1	CFST-5	120 × 120 × 3.86	31.088	200000	26700	27.3	190
2	CFST-6	120 × 120 × 3.86	31.088	200000	26700	27.3	260
3	CFST-7	120 × 120 × 3.86	31.088	200000	26700	27.3	360
4	CFST-8	120 × 120 × 3.86	31.088	200000	26700	27.3	420

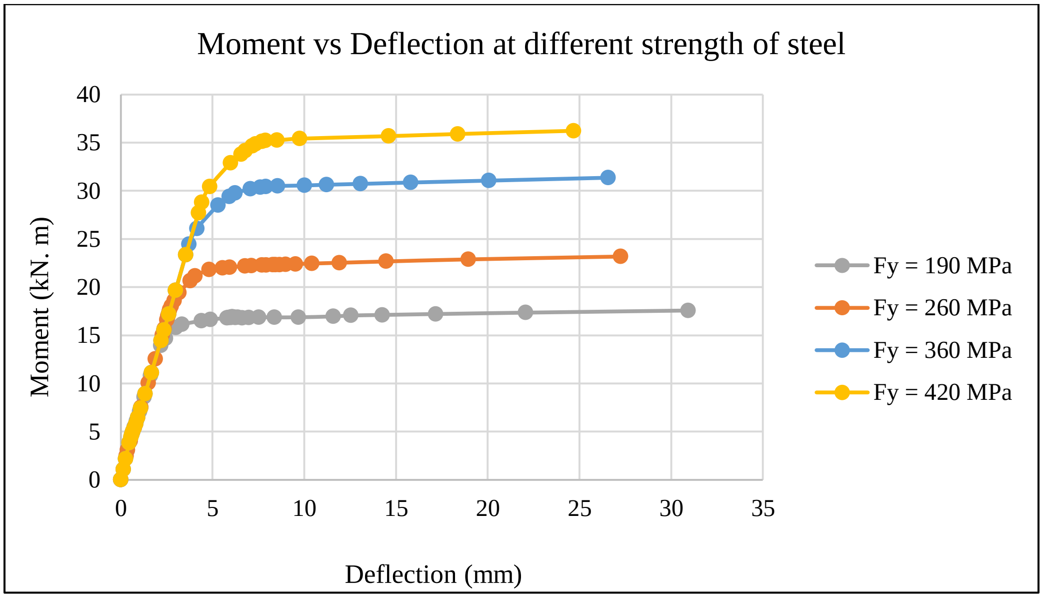

Fig. 10. Moment vs deflection for different yield strength of steel.

4.3. Effect of ultimate strength of concrete on the moment (yielding)

Simulation of the composite beam at different ultimate strength of concrete is done, to see the influence of ultimate strength on the moment (yielding). The details of specimens at different ultimate strength is shown on Table 5.

By looking at the moment vs deflection curve at ultimate strength of concrete in Figure 12, it can be seen that the moment has not been changed with the change of ultimate strength of concrete.

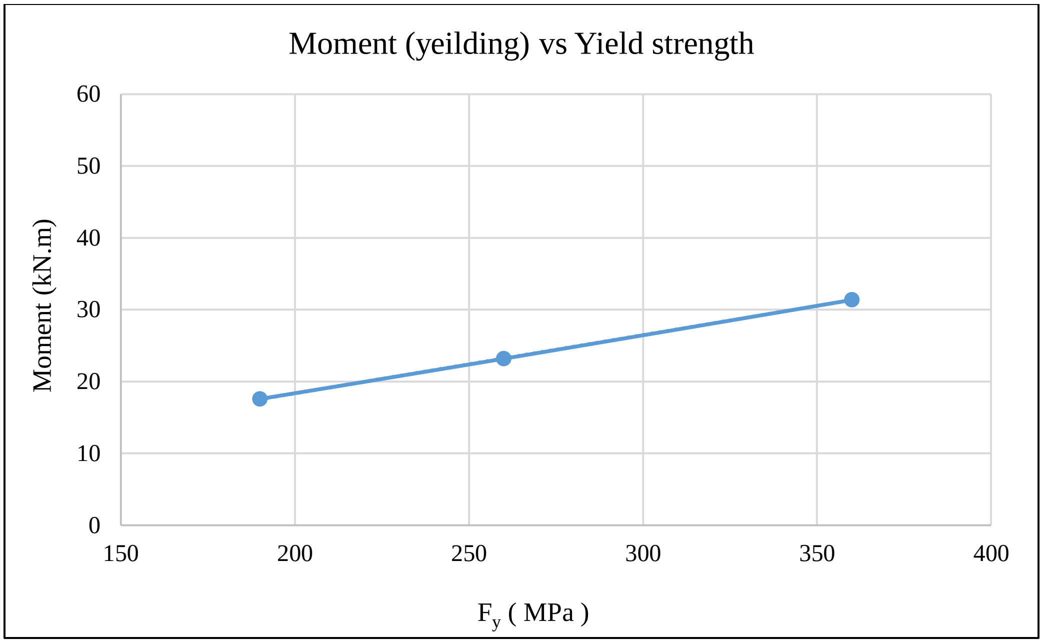

Fig. 11. Moment (yeilding) vs yield strength of steel.

Table 5.
Details of specimens for different ultimate strength of concrete

Number	Specimens label	Sectional dimension $D \times B \times T$ (mm)	$\frac{B}{T}$	E_S (Mpa)	E_c (Mpa)	F_{cu} (Mpa)	F_y (Mpa)
1	CFST-10	120 × 120 × 3.86	31.088	200000	26700	27.3	360
2	CFST-11	120 × 120 × 3.86	31.088	200000	26700	35.2	360
3	CFST-12	120 × 120 × 3.86	31.088	200000	26700	40	360

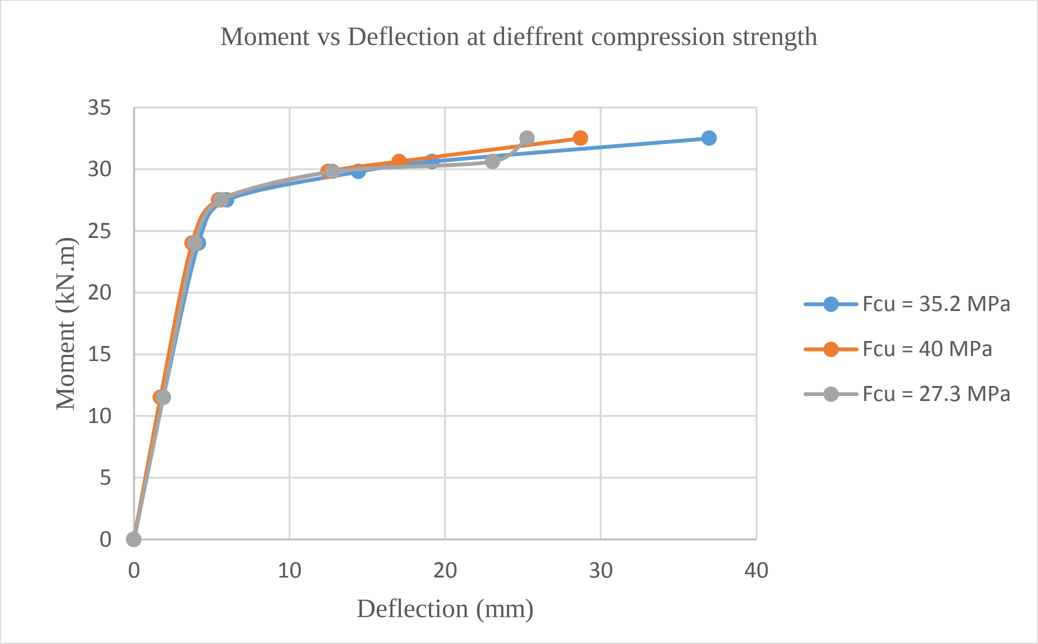

Fig. 12. Moment vs deflection for different strength of concrete.

5. Discussions

The simulation of CFST beam was carried out by using the ABAQUS and it was observed that accuracy of results depends upon the steel and concrete constitutive models. This is why, Bilinear stress strain curve for the steel was adopted instead of Elastic-perfectly plastic model. Due to the precise constitutive models, good agreement was observed between the numerical and test results of CFST beam and the failure of the beam was controlled by yielding of steel tube. It was also perceived that the strength and stiffness of CFST beam was larger than the hollow steel section due to the increase in 2nd moment of area of CFST beam. This increase in 2nd moment of area was due to existence of concrete in the CFST beam. After validation of simulation results, then the effect of width / thickness ($\frac{B}{T}$), steel tube yield strength and concrete compressive strength) on moment strength of the beam was observed for the prediction of ultimate moment(yielding) capacity of the CFST beam. The decrease of $\frac{B}{T}$ ratio, which means the increase in thickness of steel tube, results in an increase in the maximum moment capacity of the composite beam. This increase was due to large stiffness and confinement effect.

The increase in steel tube yield strength results in an increase of the maximum moment carried by the composite beam. The reason is that the failure of composite beam is governed by the failure (yielding) of steel tube. So, if yield strength of the steel tube increases, that will result in an increase in the capacity of the composite beam.

The increase in the compressive strength of concrete does not change the maximum moment capacity of the composite beam. Which proves that the capacity of the composite beam is governed by the strength of steel tube only. After parametric study, simple equations (see Equation 1 and 2) were developed to predict the moment (yielding) capacity in "kN.m" at a given $\frac{B}{T}$ ratio and yield strength (MPa)

$$M_{max} = 0.0148\,(\frac{B}{T})^2 - 1.8751\,(\frac{B}{T}) + 71.46 \quad (1)$$

$$M_{max} = 0.0811\,F_y + 2.1304 \quad (2)$$

6. Conclusions

Experiments to predict the response of steel beam filled with concrete is quite expensive and time consuming. However, in order to minimize the cost and time, finite element analysis based software can be used to model the beams. In this study, ABAQUS was used for numerical simulation of a concrete filled steel tube (CFST) beam and after validation of simulation results, the effect of width/thickness ratio, yield strength of steel tube, compressive strength of concrete and the stiffness on the moment capacity of the CFST beam were studied and following conclusions can be made from this study:

- The decrease of $\frac{B}{T}$ ratio, which means the increase in thickness of steel tube, results in an increase in the maximum moment capacity of the composite beam. The reason was that the stiffness of the composite beam was increased with the increase of the thickness of steel tube. So, the higher the stiffness, the higher moment can the composite beam take.

- Simple equation was proposed to predict the maximum moment of a composite beam at a given $\frac{B}{T}$ ratio.
- The increase in steel tube yield strength results in an increase of the maximum moment carried by the composite beam. The reason is that the failure of composite beam is governed by the failure (yielding) of steel tube. So, if yield strength of the steel tube increases, that will result in an increase in the capacity of the composite beam.
- Simple equation was proposed to predict the maximum moment of a composite beam for a given yield strength of steel. The order of the equation means that there is a linearity between the composite beam capacity and the steel tube strength.
- The increase in the compressive strength of concrete does not change the maximum moment capacity of the composite beam. Which proves the previous conclusion that the capacity of the composite beam is governed by the strength of steel tube only.
- Removal the concrete from inside the steel tube results in a decrease in the maximum moment of the composite beam. The reason was that the stiffness was reduced. This proves the second conclusion that the increase in the stiffnesses of the composite beam will result in an increase in its capacity.

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