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Flexural behavior of partially composite concrete-encased steel tubular beams

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Abstract. Composite steel-concrete construction has been widely implemented in high-rise buildings and bridges having long spans due to its favorable characteristics inherited from both materials acting as one unit. The main objective of this research is to propose a new beam system having a high strength-weight ratio, and to replace the shear studs used in composite beams by steel mesh wraps around the steel tube without any flexural or shear reinforcements. This new structural beam can be part of a lightweight-precast floor system with fast and easy ducting through its hollow tubular part. Four simply supported T-shaped beams of 3 m length are investigated experimentally to study and compare their flexural behavior. All beams are tested under two points quasi-static point loading. A comparison was initially performed between a control T-shaped reinforced concrete (RC) beam and a fully encased steel tube in a T-shaped RC beam of the same section dimensions as the control beam and without any mesh wrapping. The effect of full and partial wrapping of the steel tube was also investigated in the other two beams where 100 % and 60 % of the encased steel tube length were wrapped by a 3 mm steel mesh. Discussions and interpretation of the load-deflection behaviors and the failure modes are presented in this paper. The obtained results showed that the composite beam with unwrapped encased steel tubular section provided an advantage over the control RC beam in terms of load/weight ratio and ductility by 28.5 % and 22.4 % respectively. Besides, the use of steel mesh wraps in different length percentages revealed a much better partial composite action between the steel tube and the surrounding concrete. The attained strength ranged between 18.2 % and 33 %, whereas the ductility was enhanced by 63.8 % and up to 66.7 %.

1. Introduction

Composite construction is known in the context of civil engineering structures as the use of steel and concrete to build a single unit that exhibits better characteristics than having members made from either steel or concrete alone. Nowadays, composite construction is widely used to achieve a higher level of performance and more ductility as compared to the case of having two materials functioning separately, especially in the cases of long spans and high rise buildings [1–3]. Although a perspective approach was previously utilized in the form of codes that introduced certain limitations for the design and construction of composite structures, the guidelines provided by codes are applicable for standard shapes of composite sections. This paved the way for various researches in the domain of composite construction to investigate the composite behavior of new sections over the past years.

For instant, the American Institute for Steel Construction (AISC) [4] specifications covered two types of composite sections. The first type is related to composite beams fully encased in concrete in which the composite action depends on the natural bond between steel and concrete. The other type is related to

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composite sections in which the steel section is attached to concrete slab by mean of shear studs. However, there has been always a need for further research on composite members due to the limited guidelines provided by codes and specifications regarding new parameters or sections of interest.

Yong Liu [5] investigated the use of new type of shear connectors, alternative to the widely used studs, made from steel angles welded either to the top flanges or the web of a U-shaped steel girder infilled with concrete. All of the tested specimens were made from same span length, girder dimension, slab thickness, and steel angles. It was concluded that the installation of angles at the flange level provides full composite behavior with better ductile manner and shear transfer capacity. Also, Weng et al [6] handled the splitting shear failure in encased beams. It was concluded that the ratio of the steel flange width to that of concrete width should be less than 0.67 to avoid splitting shear failure- otherwise, shear connectors should be used.

Besides, recent studies have focused on studying static and dynamic behavior of new types of composite beams. Recently, the use of concrete filled steel tubular (CFST) beams has become increasingly studied and implemented in high rise buildings and bridges [7–11].

Furthermore, the usage of concrete encased steel tubes(CEST) is significantly increased in the building industry and especially for the case of high rise buildings accounting for advantages of ductility and high tensile strength afforded by steel, as well as, stiffness and fire resistance of concrete. One of the recent studies on CEST is done by Mohammad M. El Basha [12] to explore its flexural behavior experimentally and analytically. The main purpose of this study was to prove the possibility of having a 20 % reduction in the depth of the CEST composite section, compared to conventional reinforced concrete (RC) beam, without influencing the overall stiffness and flexural capacity. So, nine beams of 6-meter span lengths with the same reinforcement and number of shear connectors, were studied under the influence of different tube dimensions and lengths. It was found that the CEST sections had 40 % to 70 % improvement in ultimate flexural strength (directly proportional to tube depth), enhanced ductility, and increased elastic deformations compared to RC beams with the same depth and a 20 % higher depth.

In addition, Nasser H. Tuma [13] presented the flexural behavior of simply supported composite beams made from ultra-high performance reinforced concrete encasing steel tubular section. The studied parameters were related to the usage of shear connectors, location of steel tubular section, and longitudinal reinforcement ratio. It was concluded that that the flexural capacity of composite beams, with hollow tubular section and shear studs, increased significantly compared to solid RC beams and non-composite beams (without shear studs). Also, the load capacity of composite beams having tubular section located in tension zone has slightly increased (only 4 %) compared to that located at the middle of the section.

Besides, a research domain in CEST beams that gained huge interest is related to the shear behavior and splitting strength of the composite section including the effect of shear reinforcement [14–18]. One research was carried by Neelima [19] who concluded that the absence of shear reinforcement in CEST beams results in markedly increase in the crack width with concrete crushing failure in diagonal tension.

Moreover, to ensure crack control, enhanced tensile strength, concrete toughness, and improved deformation when dealing with steel-concrete composite members, fibers must be used. One of the most widely used fibers is polypropylene fiber (PP fiber) due to being non-magnetic, free of rust, alkali resistant, and widely available with cheap price compared to other fiber types. Hence several studies were lunched to investigate the effect of PP fiber on concrete workability [20], durability [21], and mechanical properties [22]. Many studies [23–25] have agreed that the recommended amount of PP fiber must be less than 1 % for best improvement in flexural strength at normal and elevated temperature.

In fact, all studies related to composite members aim to find methods to enhance the efficiency of different composite section shapes by studying several parameters. For example, [26] and [27] studied the effect of compressive strength on the flexural capacity of concrete filled steel tubular beams. Both concluded that the increase in concrete compressive strength has limited influence on the ultimate capacity of composite beams. On the other hand, [28] proved that concrete filling in hollow steel tubular beams of large scale is considered an effective method to enhance ductility and flexural performance of composite beams. Also, [29] handled a traditional method to ensure the composite action using shear studs and thus recommending that the significant enhancement in flexural capacity is maintained by positioning studs vertically on flanges.

In conclusion, the domain of composite structures has been always a source of interest to many researchers due to its complex behavior and interaction between different materials. However, the flexural behavior of composite beams made from CEST beams in the absence of any type of reinforcement and shear connectors, to satisfy the purpose of light weight- easy precast system, was not investigated yet. Therefore, the main objective of this research is to investigate the efficiency of 2 mm steel mesh wrapping around the steel tube in different locations to ensure satisfying composite action and ultimate load capacity of the specimens of interest. Also, polypropylene fiber is used in the concrete mix to provide better ductility according to recommended percentage from literature (< 2 % of cement).

2. Methods

2.1. Test Specimens and Plan

The flexural capacity of three simply supported composite beams and RC control beam of 3 m length was studied under two-point bending.

The composite specimens were made up from steel tubular section denoted by ST235 JRH and having dimensions of 160×80×4 mm totally encased in concrete in the absence of any flexural and shear reinforcement as well as shear connectors. The difference among the three specimens depends on the degree of steel-concrete interaction provided by different percentages of beam length being wrapped by 3 mm steel mesh. These percentages vary from 0 % for the case of no mesh wrapping (Fig. 1(a)) till 60 % partial wrapping and 100 % full wrapping (Fig.1 (b)). However, all specimens have the same section dimensions and deck reinforcement.

In order to prove the advantage of the studied composite beams in terms of ductility and load carrying capacity, a comparison of composite beam deprived from steel mesh (ST1) was made with traditional RC beam. The later beam has a cross section dimensions similar to ST1 beam with exactly same reinforced concrete deck reinforcements as shown in Fig. 1(c). Also, the flexural and shear reinforcement were chosen to provide close load capacity to that of ST1 beam based on analytical calculations and numerical simulation. The aim of this specimen is to show the significance of the new composite section compared to widely used reinforced concrete section in terms of strength /weight ratio.

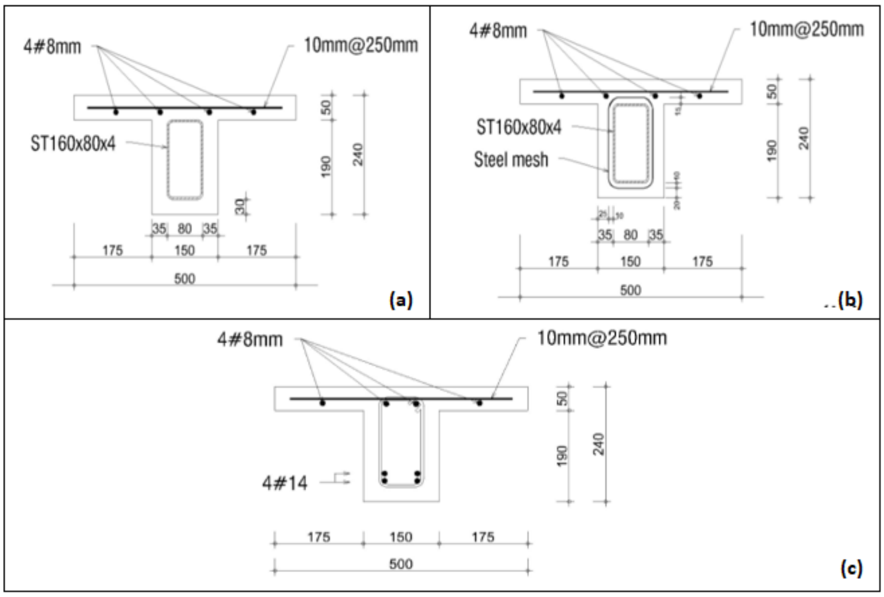

Figure 1. Cross sections of composite beams and control RC beam (dimensions in mm).

Table 1 summarizes the test plan followed in the experimental program to display the percentage of mesh wrapping in each specimen.

In addition, Fig. 2 displays the location of steel mesh wrapping along the beam length for different ST beams. As its shown, for the 60 % case of ST3 composite beam, the steel mesh was divided 45 % at the mid span and 15 % on each edge to study the influence of steel mesh at locations of high loading on the ductility and failure mode. However, for ST2 beam, full mesh wrapping was used along the entire steel tube length.

Table 1. Test Plan.

Test Group	Specimen	Length(mm)	Steel Section (mm)	Mesh (% of beam Length)	Deck Type
Control Beam	RC	3000	NA*	NA	RC
	ST1	3000	ST. 160x80x4	0%	RC
ST Beams	ST2	3000	ST. 160x80x4	100%	RC
	ST3	3000	ST. 160x80x4	60%	RC

*NA stands for not applicable case.

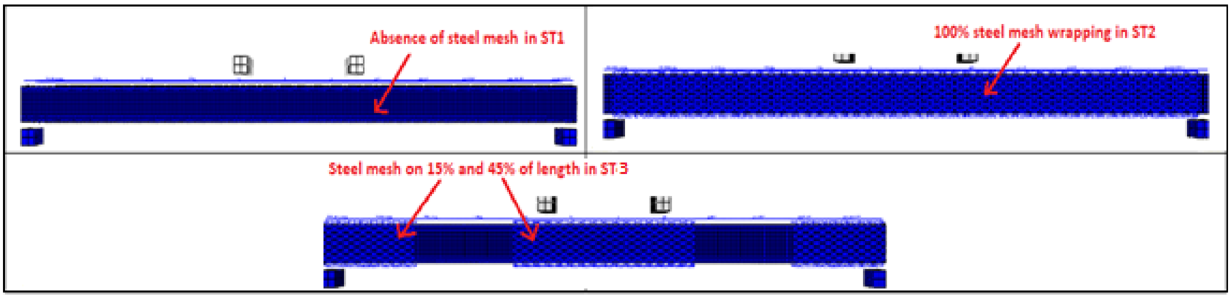

Figure 2. Steel mesh wrapping of different percentages in ST beams.

2.2. Material Properties

2.2.1. Structural Steel Tube

In this research, a steel bar of type S235JR was subjected to Coupon Tensile test at Beirut Arab University Construction Material Lab at a speed of 0.05 in-per minute till failure as shown in Fig. 3. The steel bar has the same grade of that of the steel tube used in this research. Fig. 4 (a) and (b) displays the fractured specimen at failure and stress-strain curve for the tested bar as obtained from the coupon test records. It can be noticed that the tested steel material shows good ductility based on its ability of resisting plastic deformations long before reaching its ultimate capacity. Also, the cup-cone failure ensures the ductility of the mild steel tested specimen. The obtained results of interest are summarized in Table 2.

Figure 3. Experimental setup for coupon tensile strength testing.

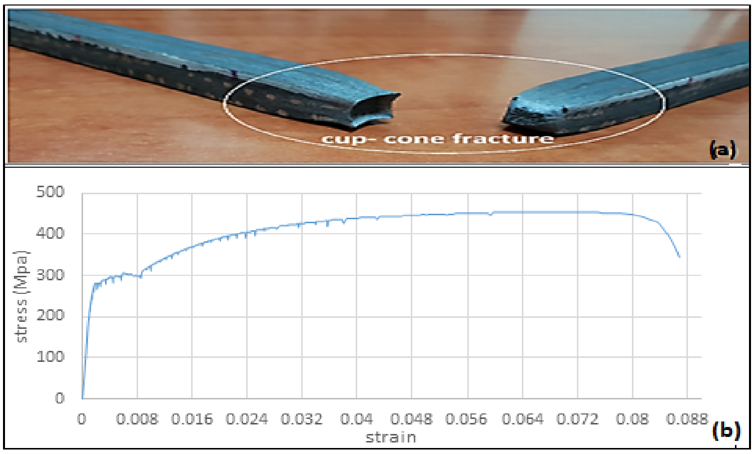

Figure 4. Coupon tensile test results: (a) fractured specimen; (b) stress-strain curve.

Table 2. Summarized results of coupon tensile test.

Steel S235JRH specimen	F_y (Mpa)	F_u (Mpa)	E_s (Mpa)	Dimensions (cm)	Δu (cm)	$\frac{\Delta u}{\Delta y}$
	280	453	198748	2×2×50.4	6.5	3.25

where, F_y, F_u, E_s, Δu, and Δy stand for yielding steel strength, ultimate steel strength, steel modulus of elasticity, ultimate deflection, and deflection at yielding strength respectively.

2.2.2. Concrete

Tables 3 and 4 summarize the aggregate properties and concrete mix proportions used in the experimental program. Cylinders of 15×30 dimensions were then taken according to ASTM C39 standards [30], cured for 28 days, and crushed at the day of testing. The average compressive strength was 24.2 Mpa.

Table 3. Aggregates properties.

Aggregate Type	Absorption(%)	Moisture (%)	Specific Gravity (g/cm^3)
Aggregate 9.5 mm	1.79	0.76	2.47
Natural Sand	1.6	2	2.68

Table 4. Concrete mix proportions for W/C = 0.5.

Material	Corrected batch weight
Cement (Kg/m^3)	350
Water (l/m^3)	180.8
9.5 mm aggregate	908
Natural sand (Kg/m^3)	887
Sikament admixture (Kg/m^3)	5.25
Fiber (Kg/m^3)	2.1

2.2.3. Steel Mesh

SSEM-04 expanded steel mesh of 3 mm thickness, shown in Fig. 5, was used in replacement of flexural rebar and shear studs to check its ability in providing good interaction with the surrounding concrete in the new composite system. In this research, the 3 mm mesh is cut in to pieces of 60 cm width each and wrapped around the steel tube with a clear cover of 1.5 cm at the top of steel flange.

Figure 5. Steel mesh wrapping around the steel tube.

2.3. Test Setup

The flexural behavior of composite beams was studied under two-point bending testing machine of Fig. 6 (a). The beam specimens were placed on two supports that were adjusted at 10 cm from the faces of the 3 m length beams. The specimens were positioned such as the web is centered over the supports while the loading pads are in contact with the reinforced concrete deck and being spaced 60 cm from each other as shown in Fig. 6(b).

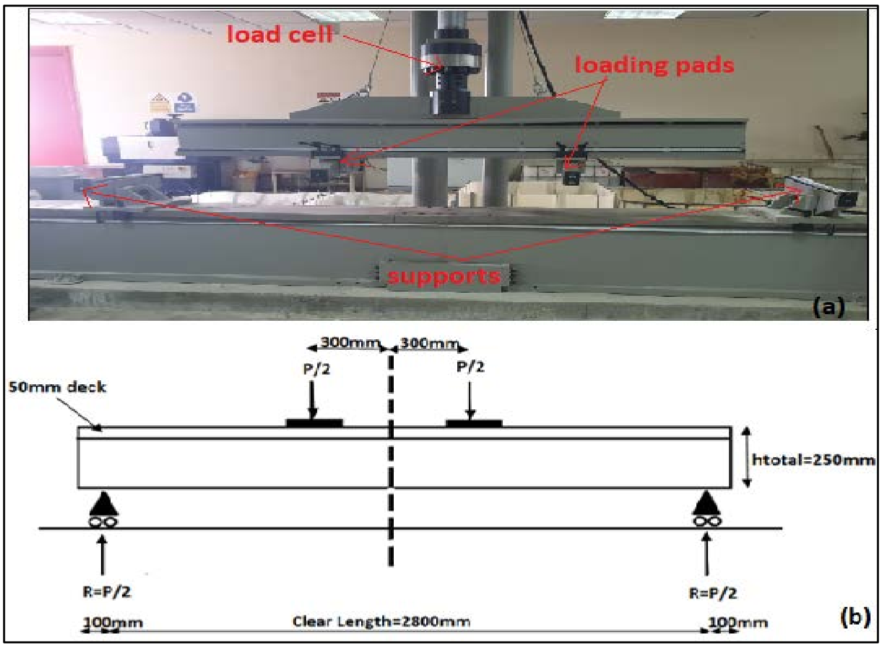

Figure 6. Test setup: (a) testing machine; (b) test schematic representation.

During the entire test, the deflection at the mid-span of the beam was recorded automatically at specific time increments using an external linear variable differential transducer (LVDT) connected to external data acquisition system as shown in Fig. 7. The rate of load increase was kept constant of 0.1 KN/sec and provided in a tabulated form by the data acquisition system connected to the testing machine as in Fig. 8.

Figure 7. LVDT Installation.

Figure 8. Data acquisition system.

3. Results and Discussion

3.1. Advantage of Studied Composite Beams

Fig. 9 shows the advantage of using composite section made from tubular structural steel with the absence of any flexural or shear reinforcement over conventional reinforced concrete beams (control beam) of same dimensions based on experimental results. For instant, at early loading stages below 10 KN, both beams experience similar stiffness. Then by increasing the load and beginning of tensile concrete cracks formation and degradation of stiffness, the composite beam showed better stiffness and capacities till reaching the ultimate capacity. In fact, the usage of ST1 beam had provided 12.7 % enhancement in the ultimate strength and 22.4 % increase in the beam ductility. For instant, the ductility was defined as the difference between the deflection records at ultimate capacities of ST1 and control beams.

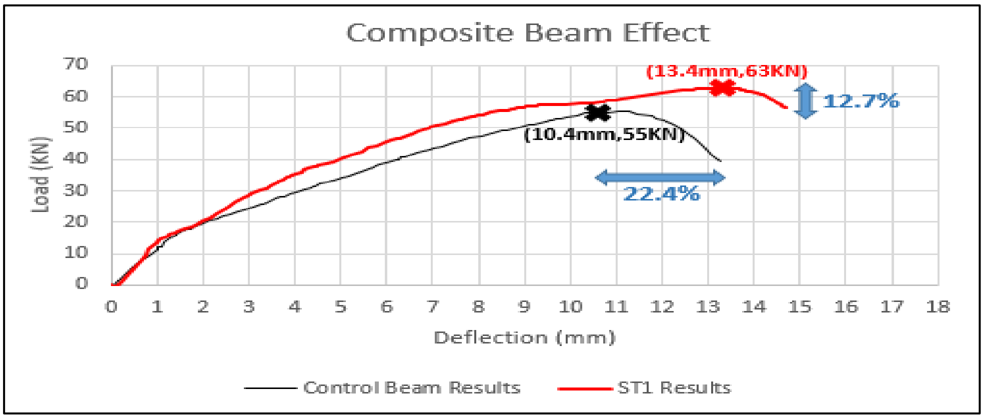

Figure 9. Comparison of load-deflection curves of control beam and ST1 composite beam.

In addition, by comparing the *load-weight* ratio of these two beams we found the ratio of RC beam is: $\frac{55KN}{519.5Kg} = 0.1058$ and for SP1 beam : $\frac{63KN}{424Kg} = 0.148$. Based on these values, it was obtained that the usage of ST1 beam has modified the capacity to weight ratio by 28.5 % as well as providing easy passage of ducts**,** so our aim of checking the practical implementation of this section as part of long span precast floor system having high strength-weight ratio is achieved.

The obtained results gave a motivation to study the effect of using steel mesh of relatively low weight on enhancing the flexural behavior more.

3.2. Effect of Steel Mesh on Strength and Ductility

As it can be noticed from Fig. 10, the usage of steel mesh wrapping around the structural steel section prior to casting plays an important role in enhancing the ultimate capacity of the composite beam as well as the corresponding ductility. For instant, at low loading values, all the composite beams that are made from steel tubular section or hollow pipe section, have same stiffness. However, by increasing the applied load, degradation in material stiffness was obvious from the reduction in slopes till reaching ultimate capacity at different deflection records.

Comparing the ultimate capacity of composite beams with steel wrapping versus ST1 beam (0 % mesh), we can see that the ultimate loading capacity has increased by increasing the length of mesh wrapped around the structural steel. This increase was significant in beam ST2 (32.98 %) and noticeable in ST3 beam (18.18 %).

Besides, the ductility has improved significantly by the usage of wrapped steel mesh. It increased by 63.78 %, and 66.71 % due to increasing the percentage of mesh used to 60 % and 100 % respectively.

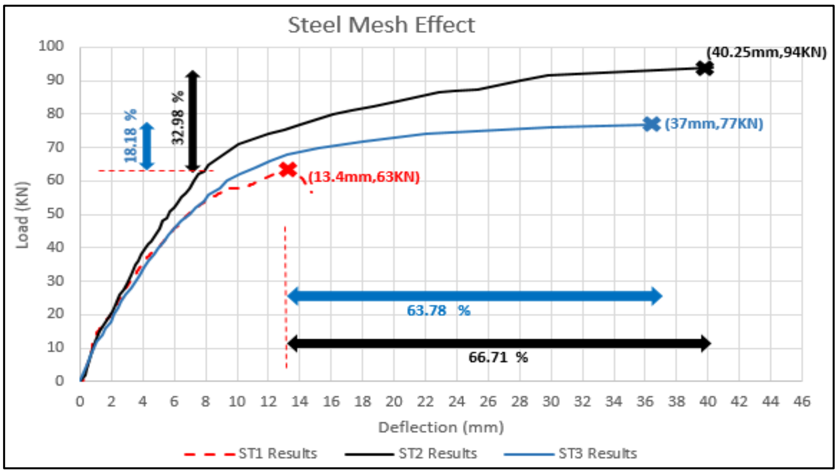

Figure 10. Comparison of load-deflection curves of ST1, ST2, and ST3 composite beams.

These results also display the advantage of steel mesh as one piece on the entire beam length by providing better bond, reducing relative deformation between beam parts, and thus enhancing the capacity and ductility. Also, composite beam ST3 of 60 % wrapping can be considered as optimized specimen since it has acceptable enhancement in ultimate capacity compared to ST1 case and very close ductility improvement to the case of full mesh wrapping in ST2 beam. In this comparison, the ductility was also defined as the difference between the deflection records at ultimate capacities of different mesh-wrapped composite beams relative to ST1 beam.

3.3. Effect of Steel Mesh on Failure Mode

Comparing the failure modes of composite beams made from steel tubular sections in Fig. 11, we can check the importance of steel mesh on the flexural behavior and ductility of the studied beams. In fact, the absence of steel mesh in Fig. 11 (a) has led to wide horizontal crack propagation till concrete spalling at the edges of the beam with some flexural cracks at mid-span as the applied load reached the ultimate capacity. On the other hand, Fig.11 (c) proves that the usage of steel mesh at the location of mid span and edges (ST4 beam) provided better ductility on the entire length of the beam due to generation of many fine flexural cracks at meshed zones and prevented spalling at the edges due to the presence of steel mesh. So, the failure in ST3 beam was due to widening of two tensile cracks in the unmeshed zone and their propagation below the deck. In addition, Fig. 11 (b) satisfies the advantage of steel mesh by providing best ductile behavior of cracks being distributed on the entire beam length and no spalling of concrete with a small slippage at the edges of the beam of 0.5 cm. Hence, the presence of wrapped steel mesh provided favorable ductile failure mode.

Based on the drawn analysis, the influence of steel mesh wrapped at the edges of the steel tube only or at the mid span needs further investigation to better understand the influence of steel mesh on each location separately.

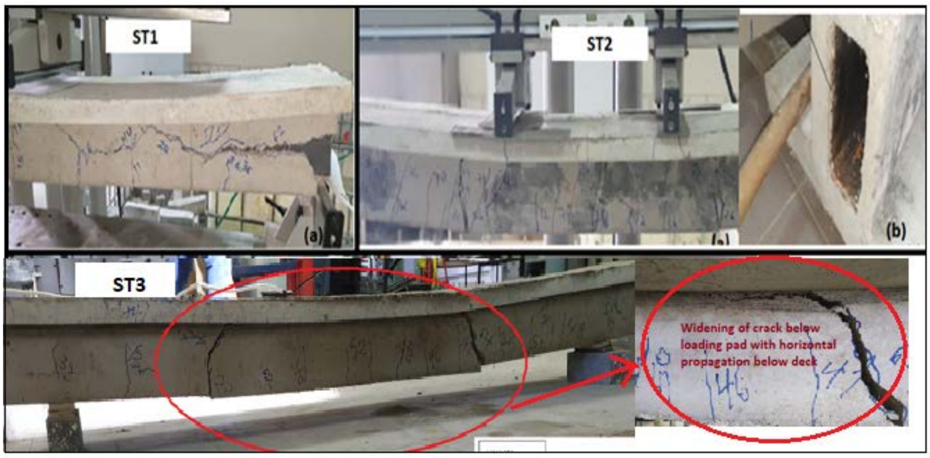

Figure 11. Comparison of failure modes of ST1, ST2, and ST3 composite beams.

3.4. Comparison to other Research

Since the experimental setup is applicable to a limited range of section dimensions and being working with relatively new section regarding the absence of any shear and longitudinal reinforcement with the implementation of steel mesh wrapping to ensure steel-concrete interaction, there is no similar previous research to compare results to. However, steel mesh wrapping can be considered as an alternative efficient method to enhance the strength and ductility of composite beams as compared to previous parameters mentioned in the state of art.

4. Conclusion

The flexural behavior of an innovative composite joist, made from steel tubular section totally encased in concrete in the absence of flexural reinforcement and shear connector, was experimentally studied using a two–point bending test. The following conclusions can be drawn:

1. The studied composite beam made from steel tubular section without mesh wrapping showed advantage over conventional RC beam of same dimensions in terms of enhanced strength/weight ratio and ductility by 28.5 % and 22.4 % respectively.

2. The studied composite beams can be used as part of light weight-high strength precast floor system as a replacement of higher weight reinforced concrete system of a close capacity.

3. As the percentage of beam length being covered with mesh increases, the ultimate capacity and ductility increases up to maximum values of 66.7 % and 32.98 %,respectively, for the case of full mesh wrapping versus no mesh in ST beams.

4. The fully wrapped composite beams experienced the best ductility and load capacity due to maintaining almost full bond between the steel tube and the surrounding concrete by using the steel mesh on full length. Thus preventing large relative slippage between all components and attaining excellent bonding.

5. The presence of steel mesh at the beam edges is critical for preventing the formation of horizontal cracks near the edges and concrete splitting.

6. Although full mesh wrapping in ST specimens provided best ductility and capacity results, yet the 60 % mesh wrapping can be considered as optimized section for designers by having a small difference in capacity and ductility compared to full mesh wrapped sections (15 % maximum difference).

7. The proposed composite beam can be used as part of precast floor system having advantage of high strength-weight ratio. It can be easily prefabricated and rapidly erected with the privilege of being economic by replacing the usually used shear studs with the light steel mesh.

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