DUCTILE BEHAVIOR OF SHALLOW FLOOR COMPOSITE BEAMS

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SUMMARY

Ductility is an important property for the design of flexural members and most rules are based on the assumption that adequate ductility is available. However, securing that the desired ductility level can be realized is not a simple task for composite beams. The rules of EN 1993-1-1 referring to steel can be adopted but, for the case of concrete filled shallow floor (SF)-beams they are very conservative and may lead to uneconomic designs. In this paper, the results of a test campaign regarding 3-point bending tests on SF-beams in different configurations are presented. The importance of correct detailing is critically reviewed and preliminary methods for enhancing the ductility of SF-beams are discussed.

1. INTRODUCTION

Deltabeams are slim-floor composite beams that are integrated into the floor. The beams are completely filled with concrete on-site, through regularly spaced web openings and they form a composite structure after the concrete has hardened.

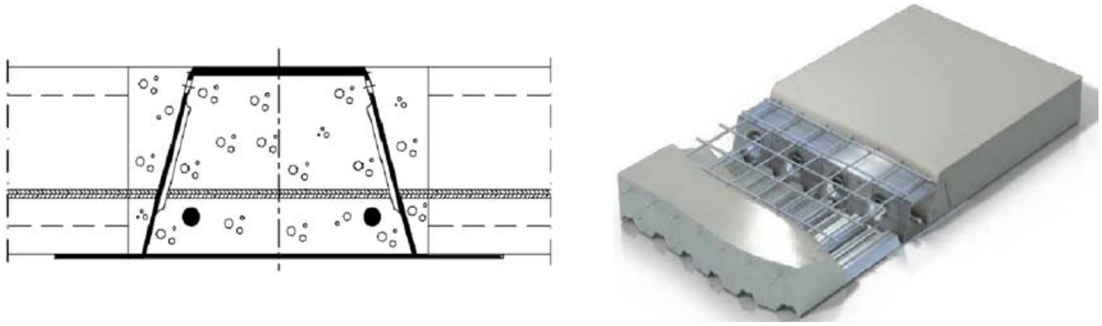


Figure 1 Typical section of Deltabeam

The vertical shear resistance of the composite cross-section is considerably higher than that of the steel part because of the contribution of the core concrete. Findings from the investigation of the shear strength of Deltabeams are reported by Leskela et al. in [5]. Deltabeams have also high values of fire resistance (rate higher than R180), depending on the thickness of the bottom plate and the amount of fire rebars inside the boxed section. Frequently, the contribution of fire rebars is higher than 50 ~ 70 % of the bending capacity in typical beam sections [9]. Experimental investigations on the fire resistance of Deltabeams equipped with hollow core slabs are found in [3]. Numerical findings on progressive collapse of buildings with Deltabeams, which are published in [4], show that Deltabeams, because of their high shear and bending capacity, can be an effective solution for buildings that need to be designed against column loss scenarios.

2. INVESTIGATION OF BENDING BEHAVIOR OF DELTABEAMS

2.1 Scope of the tests

An on-going investigation regarding the bending behaviour of Deltabeams was initiated at the National Technical University of Athens. The tests are conducted in the Institute of Steel Structures of NTUA. In this paper, the results of 12 specimens with various geometry and reinforcing details under 3-point sagging bending tests are presented.

2.2 Test set-up

The experimental set-up consists of a test rig, a computer controlled hydraulic cylinder and test specimens. The test rig available in the Steel Structures Laboratory of NTUA was appropriately modified to receive the test specimens. It consists of four large columns resting on the strong floor of the Laboratory that are connected in both directions by rolled and built-up steel beams (Fig. 2). The supporting conditions for the specimens should represent “hinged” supports, free of longitudinal restrain. Thus, the supports were accordingly specifically designed and fabricated for these tests (Fig. 2). Their design provided a rigid vertical support along the entire specimen width, free development of end rotations and frees longitudinal sliding of the specimen. The end supports were used for all specimen heights without movement of the actuator. Accordingly, the supports were designed as a rigid stiffened steel structure anchored at the strong floor. Free rotation was allowed by a steel cylinder located between two semi-circular guides, while free sliding through the provision of a stainless steel plate resting on Teflon. The support construction was restrained in longitudinal direction by two horizontal braces. The width of the end supports was such that the system length of the test specimen between support axes was 7200 mm. The actuator is a computer controlled hydraulic cylinder with a load capacity of 2.5MN and a maximum stroke of 500 mm positioned vertically on a rigid beam. The load was introduced to the specimen by means of a rigid construction. The dimensions of the contact area between the rigid load introduction and the specimen were 250 x 350 mm in the longitudinal and transverse direction correspondingly.

Figure 2 Test set-up, Detail of load transfer and specimens supporting structure

2.3 Experimental measurements

The experimental measurements include deflection, strain, slip and rotation measurements as described in the following. The recordings of all instruments were set to zero (0) immediately before the start of the loading protocol. Accordingly, all measurements do not include the effects of the self-weight of the test beams. They include only the effects of the applied concentrated load.

For the deflection measurement at mid-span and at the end supports an aluminum bar with an angle section was placed transversely to the specimen at mid-span and supported by magnets to the specimens steel flange. This was the top flange for specimens S1 and S12 and the bottom flange for the rest of the specimens. The deflections on both sides of the specimens at mid-span were measured by transducers resting on the floor that were connected to this transverse angle. In addition, the settlement of the supports was measured by LVDTs. The measurements indicated that these deformations were negligible, in the order of magnitude 1.5 mm at maximum load, where the specimen deflections were 450 mm.

Regarding the strain of the steel flanges, measurements were taken at sections A and B on both sides of the loaded area at a mutual distance of 700 mm. Strains are measured at two positions of the flanges (Fig. 3) for specimen S1, S11 and S12, i.e. 8 measurements, where there is access to both flanges, whereas for specimens S2 to S10 only at three positions of the bottom flanges to which there was access, i.e., 6 measurements. In addition, for specimens S2 to S11, compressive strains of the concrete are measured in the loaded area at a base length of 700 mm (Fig. 4). The measurements were performed by LVDTs between aluminum angles that were fastened 40 mm below the top surface of the concrete. Finally, the slip between concrete and steel flanges was measured at six sections (Fig. 5), three on each side of the specimen, coincident with the positions of the holes at the webs of the box. For specimens S1, S11 and S12 the slip was measured at the top flanges, whereas for specimens S2 to S10 at the bottom flanges. Subsequently, steel angles were mounted by magnets at exactly the same position as the aluminum angles. Slip was measured by LVDTs which were fasten to the steel angles and were connected to the aluminum bars.

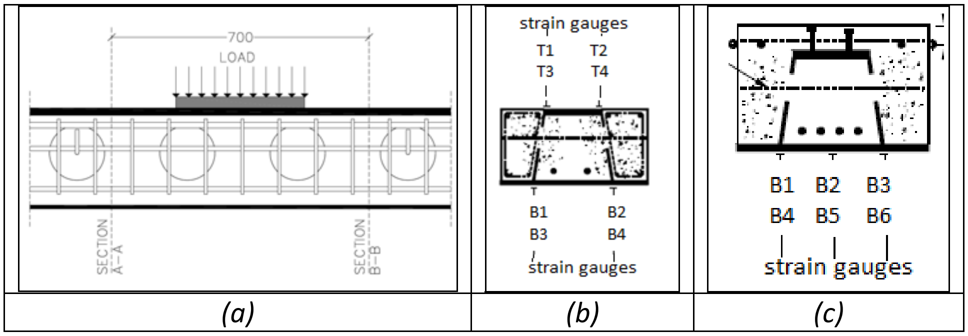


Figure 3 Strain measurements of the steel flanges a) in longitudinal direction and in transverse direction b) for specimens S1, S11 and S12 and c) for specimens S2 to S10

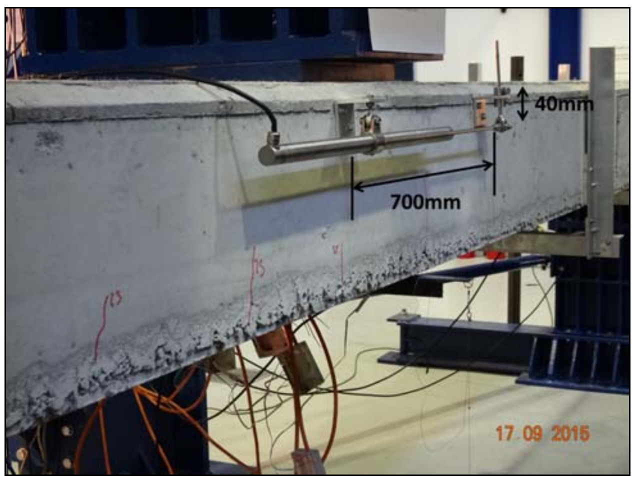


Figure 4 Strain measurements of concrete in the loaded area

Figure 5 Slip measurements between steel and concrete a) for specimens S1, S11 and S12 and b) for specimens S2 to S10

2.4 Loading Protocol

Loading was introduced displacement-controlled. Two loading protocols were used (Fig.

6). The first one, used for tests S1 to S6a, included three (3) cycles at serviceability displacements 27 mm, which is approximately L/260. Consequently, the displacement was increased with two different speeds, one slower in the range 0 to 100 mm and one faster in the range 100 to 450 mm. The duration of each loading-unloading phase for the three 3 cycles was 7.5+2.5=10 minutes, the duration of loading in the range 0 – 100 mm and in the range 100 – 450 mm was 1 hour. The total duration of the test was accordingly 2 ½ hours. The loading speed for the 3 cycles was 0.06 mm/sec, in the range 0 – 100 mm 0.0278 mm/sec and in the range 100 – 450 mm 0.0972 mm/sec. The second loading protocol was applied for the rest of the tests (S6b and S7 to S11). It included also three (3) cycles for serviceability displacements 27 mm and after that the displacement was increased with two different speeds, one slower in the range 0 to 150 mm and one faster in the range 150 to 450 mm. The duration of each loading-unloading phase for the three 3 cycles was 7.5+2.5=10 minutes, the duration of loading in the range 0 – 150 mm was 1 ½ hour and in the range 150 – 450 mm was 1 hour. The total duration of the test was 3 hours accordingly. The loading speed for the 3 cycles was 0.06 mm/sec, in the range 0 – 150 mm 0.0278 mm/sec and in the range 150 – 450 mm 0.0972 mm/sec.

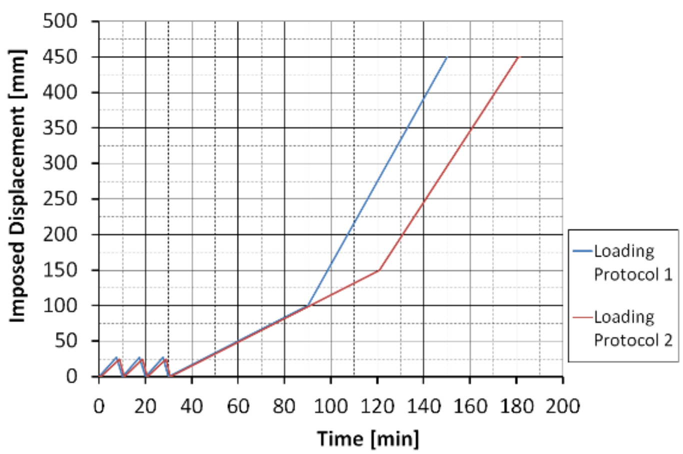


Figure 6 Loading Protocols

2.5 Test specimens

The specimens were divided in four types regarding the detailing of their section (Fig. 7). With these four types, various parameters like different steel profiles, reinforcing details, arrays of shear studs and concrete shapes were investigated during the experiments. The concrete used in the specimens is C30/37 according to EN 1992-1-1 [1] and the material for the steel part is S355J2+N according to EN 10025-1:2004 [2].

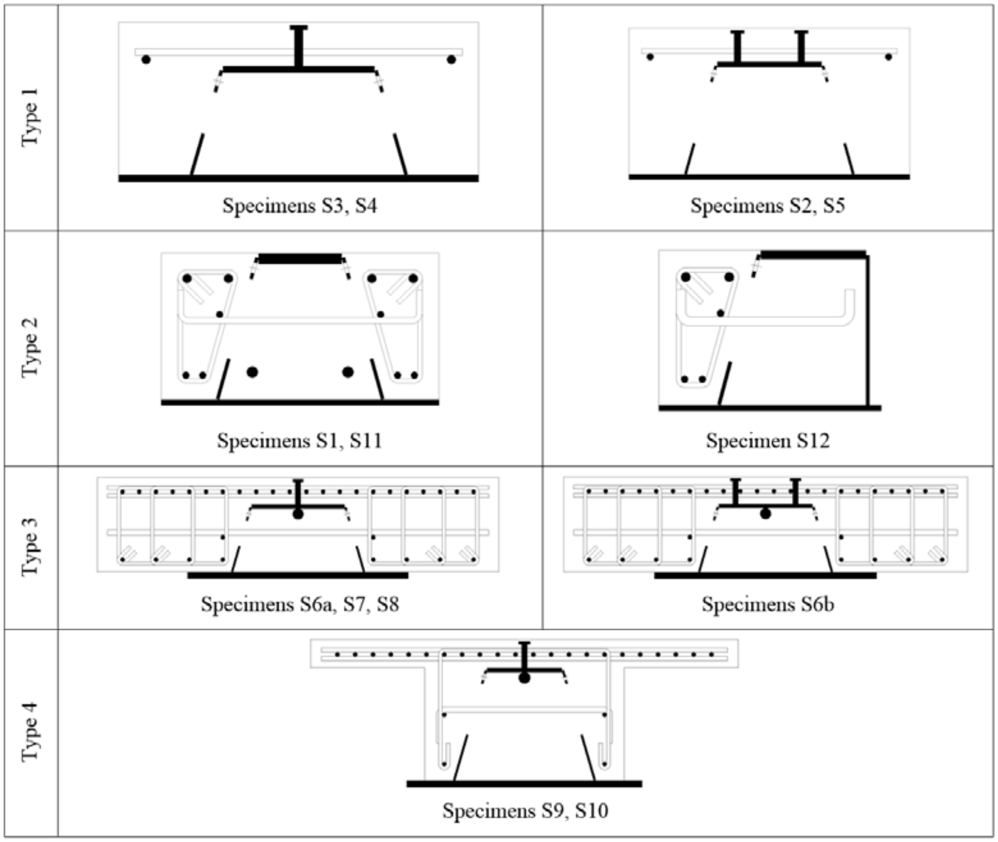
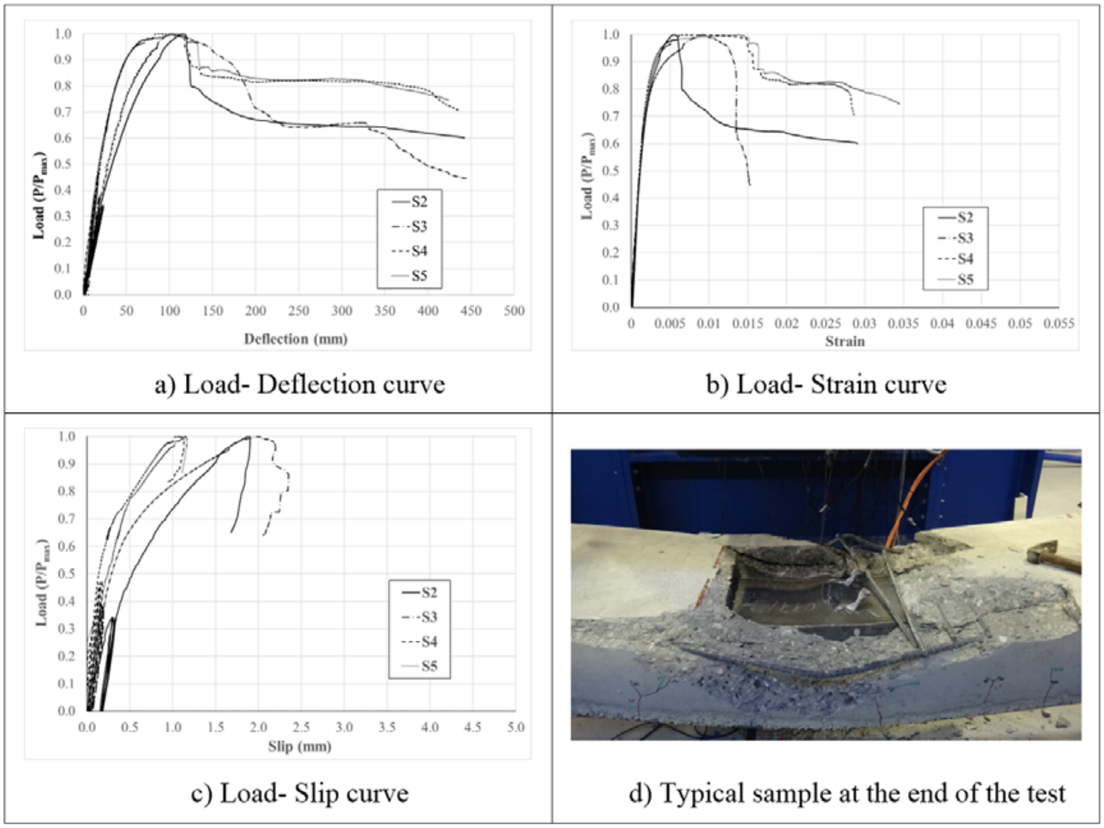


Figure 7 Section details of specimens

3. RESULTS

3.1 Type 1 Sections

Type 1 sections refer to the specimens with the smallest reinforcement. This factor had a greatly influential effect on their behavior as demonstrated in the graphs of Fig. 8. After the application of the maximum load, all specimens experienced strength degradation (Fig. 8a) and because of the lack of sufficient longitudinal and transverse reinforcement the crushing of the concrete under compression was inevitable. This lead to a wide spalling area of the concrete and after the outer concrete was crushed, the transfer of the transverse load was no longer fisible and the top and web plates buckled (Fig. 8d).



a) Load- Deflection curve

b) Load- Strain curve

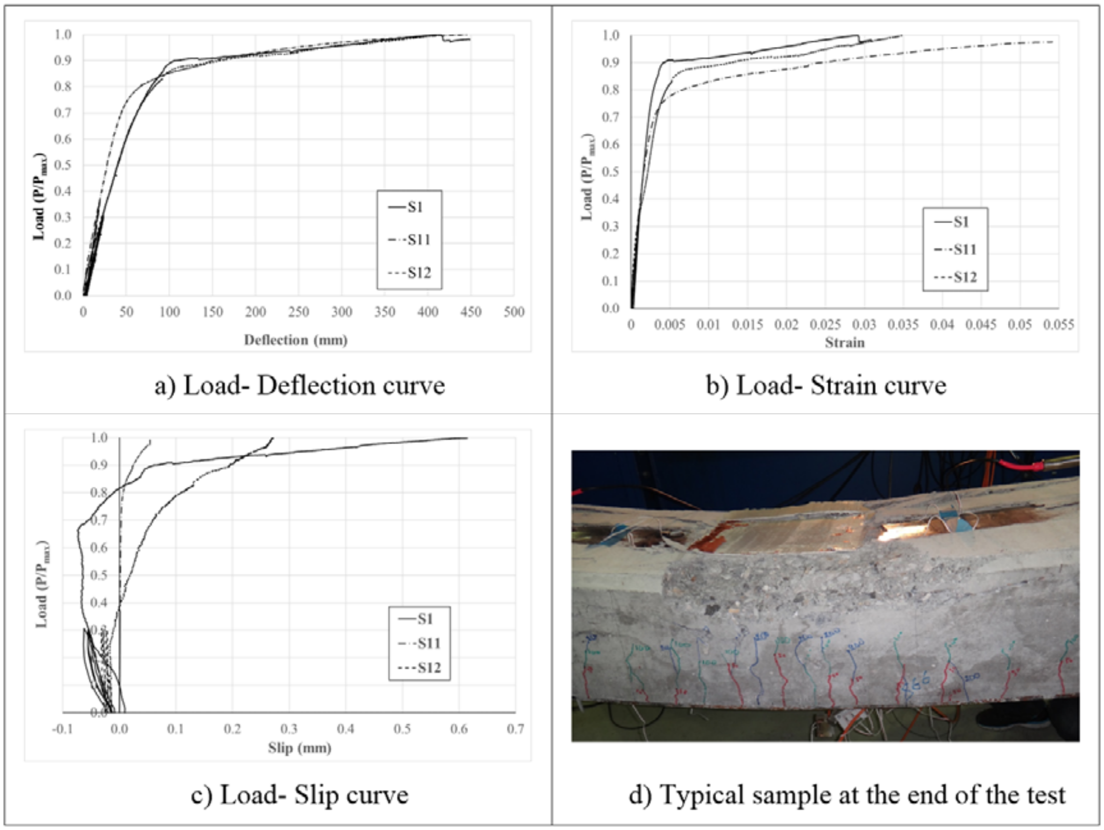
c) Load- Slip curve

d) Typical sample at the end of the test

Figure 8. Results of Type 1 sections

3.2 Type 2 Sections

The force-displacement curves are shown in Fig. 9a. All specimens demonstrated a hardening behavior with no strength degradation. In all three tests, each experiment was terminated before the maximum load capacity of the specimens was achieved, because the maximum displacement capacity of the loading actuator was reached. By assuming that the yielding load is equal to 75% of the maximum force, the displacement ductility values for S1, S11 and S12 are equal to 6.4, 9.0 and 6.0, respectively. The fact that the hardening behavior is maintained up to the end of the tests (approximately 450mm) indicated that even higher ductility values could be achieved. This argument is enhanced by the fact that all specimens were at excellent condition after the completion of the tests, since undesired phenomena, like extended failure of the concrete or buckling of the plate or rebar did not occur (Fig. 9d). This can be attributed mostly to the confinement effect in the core concrete inside the steel section and the dense stirrups that keep the external concrete intact.



a) Load- Deflection curve

b) Load- Strain curve

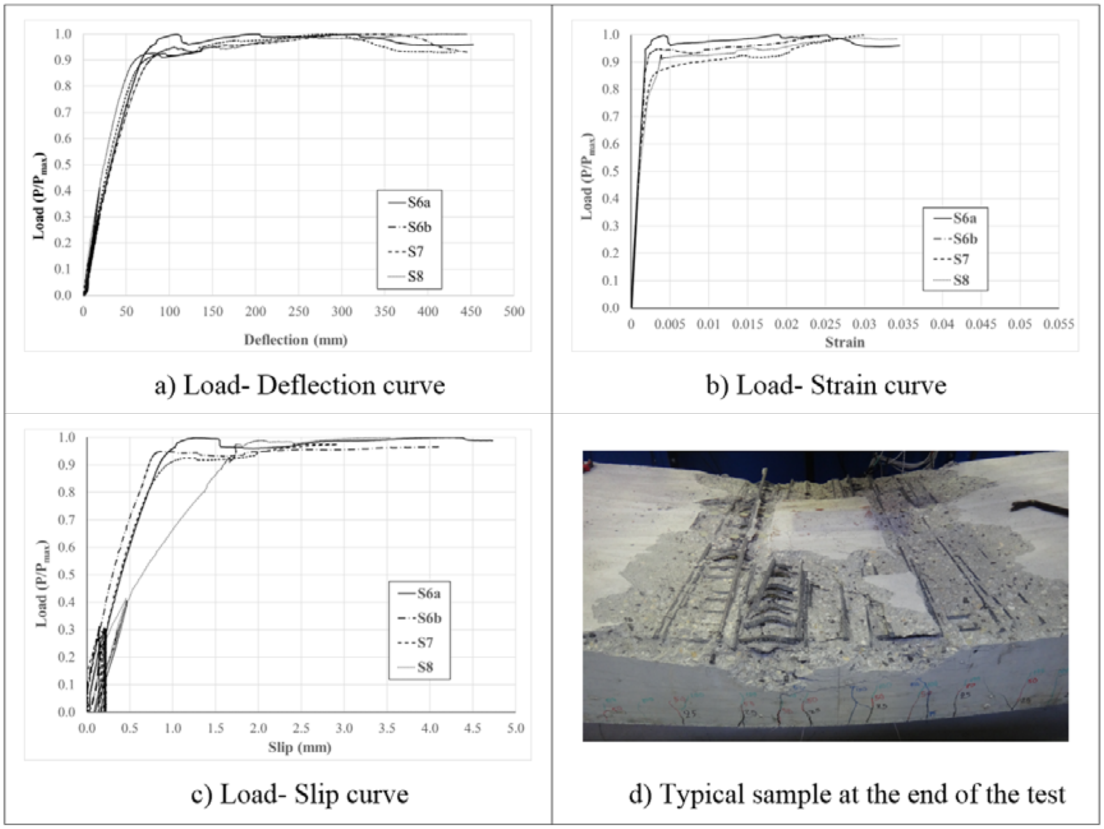
c) Load- Slip curve

d) Typical sample at the end of the test

Figure 9 Results of Type 2 sections

3.3 Type 3 Sections

The tests with the Type 3 sections also provided satisfactory results. The beams demonstrated hardening behavior with no strength degradation and only small strength reductions were caused by local crushing of the concrete. These crushed areas were limited to the top cover of the concrete plate because of the fine reinforcing details and the confinement provided by the stirrups (Fig. 10d). Again, the tests were terminated at a maximum displacement capacity of the actuator at approximately 450 mm. Ductility values ranged between 6.9 to 10.



a) Load- Deflection curve

b) Load- Strain curve

c) Load- Slip curve

d) Typical sample at the end of the test

Figure 10 Results of Type 3 sections

3.4 Type 4 Sections

In order to describe the behavior of these specimens, the force- displacement curves were divided into three parts. The first part was up to the maximum load at a deflection equal to 90 mm. At that point, the first concrete ledge of the plate reached failure. After a small strength reduction, about 5%, the curve remained constant until deflections of 200 mm and 175 mm for S9 and S10 were reached, respectively. Then the second concrete ledge failed leading to an additional drop of strength equal again to 5%. After that point the strength was maintained at that level until the end of the tests providing again an overall ductile behavior. This behavior can be explained by taking into account the contribution of confinement attributed to stirrups that kept the central part of the section in a perfect shape, preventing unwanted local phenomena.

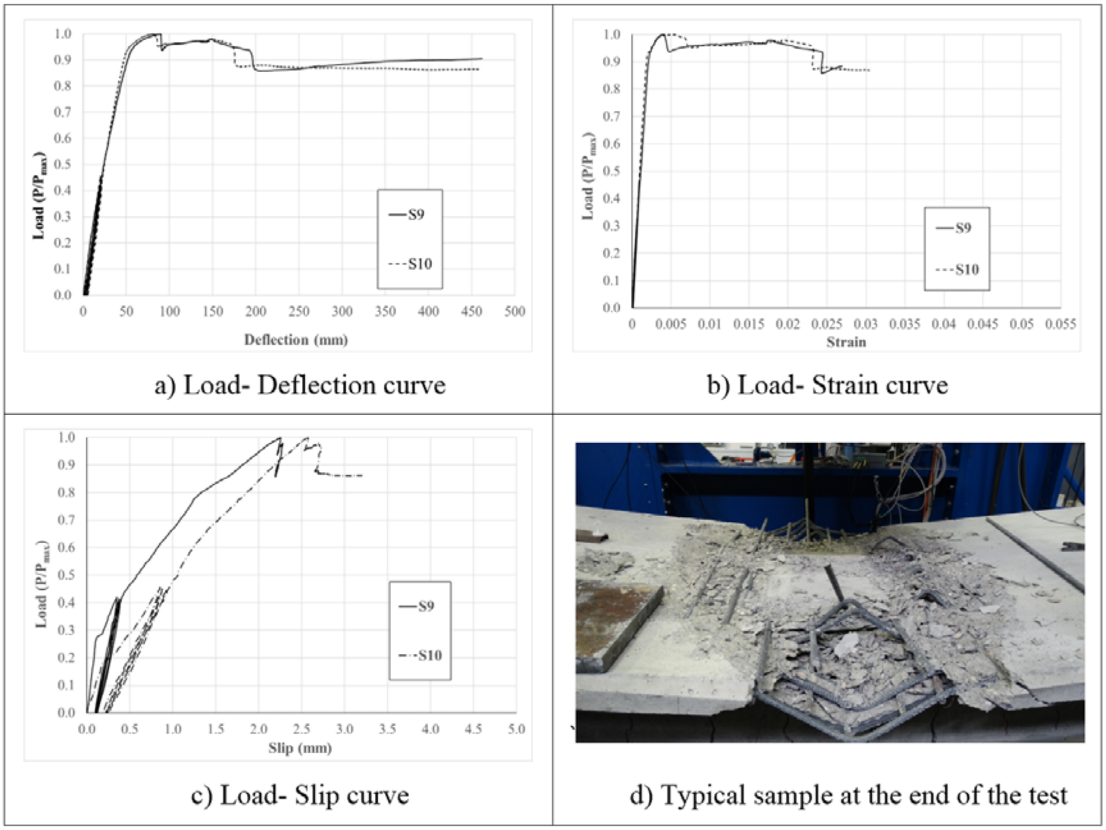


Figure 11 Results of Type 4 sections

4. CONCLUSIONS

The bending behavior of a series of 12 boxed-shaped steel cross-sections encased in concrete was investigated by means of three-point-bending tests and the results are presented here. The results showed that the composite beams (Deltabeams), in conjunction with proper steel reinforcement offer an extremely ductile behavior. The slips between concrete and structural steel were very small and the integrity of the specimens was maintained up to the end of the tests. The beneficial structural response indicates that such properly reinforced slim floor beams can be implemented by the designers not only for typical ultimate state design but also for extreme cases, such as progressive collapse and accidental loadings.

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ΠΕΡΙΛΗΨΗ

Μια σημαντική ιδιότητα στον σχεδιασμό έναντι κάμψης είναι η πλαστιμότητα, καθώς οι περισσότεροι κανόνες σχεδιασμού βασίζονται στην παραδοχή ότι υπάρχει διαθέσιμη επαρκής πλαστιμότητα. Ωστόσο σε πολλές περιπτώσεις η εξασφάλιση μέσω υπολογισμών επαρκούς πλαστιμότητας δεν είναι εύκολη, καθώς δεν υπάρχουν διαθέσιμοι κανονισμοί. Στην περίπτωση των Deltabeams θα μπορούσαν να χρησιμοποιηθούν οι κανόνες που παρέχονται στα πλαίσια του EN 1993-1-1, οι οποίοι όμως αναφέρονται σε δομικό χάλυβα και όχι σε εγκιβωτισμένες σύμμικτες δοκούς, με αποτέλεσμα να είναι αρκετά συντηρητικοί και να οδηγούν με την χρήση τους σε αντιοικονομικούς σχεδιασμούς. Στην παρούσα εργασία, παρουσιάζονται τα αποτελέσματα πειραμάτων κάμψης τριών σημείων σε εγκιβωτισμένες σύμμικτες δοκούς διαφόρων διατομών (Deltabeams), μέσα από τα οποία εξετάζεται η σημασία του σωστού σχεδιασμού των λεπτομερειών. Τέλος παρουσιάζονται προκαταρκτικές μέθοδοι αύξησης της πλαστημότητας των σύμμικτων δοκών εγκιβωτισμένων σε σκυρόδεμα.