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Citation: Tsavdaridis, K. D., D'Mello, C. & Hawes, M. (2009). Experimental Study of Ultra Shallow Floor Beams (USFB) with Perforated Steel Sections. Paper presented at the Nordic Steel Construction Conference 2009 - NSCC2009, 02-09-2009 - 04-09-2009, Malmö, Sweden.

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Experimental Study of Ultra Shallow Floor Beams with Perforated Steel Sections

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ABSTRACT: In modern building construction design, floor spans are becoming longer. Hence, steel framed structures have become more competitive when compared with traditional reinforced concrete framed buildings. In order to minimise the structural section of the composite sections, and for economic reasons, steel perforated beams are designed to act compositely with the floor slab. When the concrete slab lies within the steel flanges, as in the Ultra Shallow Floor Beam (USFB), there is an additional benefit when considering fire resistance. The aim of this study is to investigate the contribution of the concrete in composite cellular beams in the case where the concrete slab lies between the beam flanges of a steel section, when resisting vertical shear forces. The concrete between the flanges enhances the load-carrying capacity by providing a load path to transfer the shear force. Four specimens of steel-concrete composite beams with web openings in the steel section were tested in this study. One bare steel section with web openings was also tested as a comparison. This is the first such investigation of the failure mode under shear resistance (Vierendeel action) of the Ultra Shallow Floor Beam. In the test specimens, the web opening diameter is 76% of the beam depth, which is the largest currently available. This represents the worst case in terms of Vierendeel bending forces generated in the vicinity of the web openings. The smaller the hole is, the easier it is for the trapped concrete between the flanges to transfer shear across the opening. The results from the composite beam tests show a significant increase in shear resistance. The percentage of the shear capacity improvement of the particular case is presented herein as well as the failure mode of the composite beams. The shear enhancement demonstrated in this study has been utilised software that is used in design practice.

1 INTRODUCTION

1.1 *Real floor system*

The Ultra Shallow Floor Beam (USFB) is a new type of composite floor beam and was developed by Westok Ltd. The steel section is fabricated by welding two highly asymmetric cellular tees together along the webs resulting in a large bottom flange. Either precast concrete floor units or profiled steel decking rest on the bottom flange of the USFB creating a very shallow floor beam construction system, thus minimising the overall structural depth. A special end diaphragm is used for deep decking floor applications so that the concrete fully surrounds the steel section, apart from the bottom plate. 'Arching' action is occurred through the concrete partial encasement, which is re-

sisted by the end plate connections. The web openings provide a passage for reinforcing tie bars and service ducts within the depth of the beam. In-situ concrete fills the web openings as the floor slabs are cast. This concrete passing through the web openings, together with the reinforcing bars and ducts, contribute to the longitudinal shear resistance when the beam is subjected to axial bending.

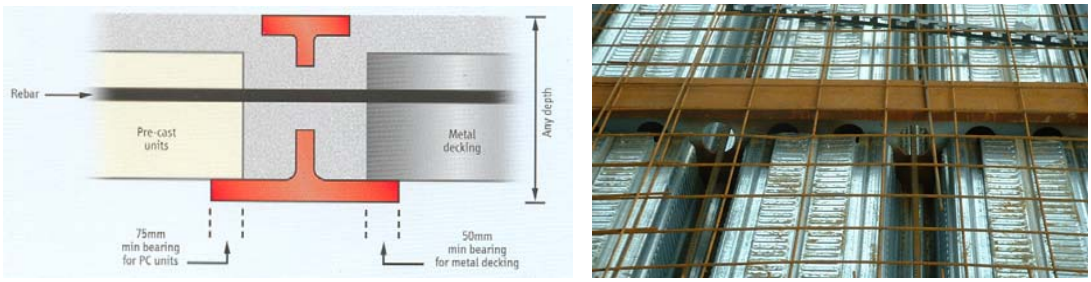

Figure 1. Cross-section configuration of USFB (left) and deep decking floor application (right) adopted by Westok Ltd.

1.2 *Objectives*

The main aim of the study is to determine the enhanced vertical shear capacity of composite perforated beams where the concrete slab lies within the steel flanges, when compared to bare steel beams. In addition; the failure modes of the composite and non-composite sections are investigated. The worst case scenario is examined herein without any mechanical shear connection between the steel and the concrete, thus providing the most conservative results. As the results from this study are to be used in design practice, recommendations on the allowable nominal shear have been made. (BS 8110: Part 1: 1985)

1.3 *Scope of the work*

The work reported here is on an experimental investigation of the vertical shear behaviour of composite cellular beams. The investigation focuses on the enhanced behaviour of the capacity of the tee-sections at the holes, due to the concrete infill between the flanges of the steel beams. Four composite USFBs and one non-composite steel beam with the same dimensions were tested in this study. Hence, with the same structural and loading arrangement, a direct comparison is made. The loading arrangement is shown in Figure 2.

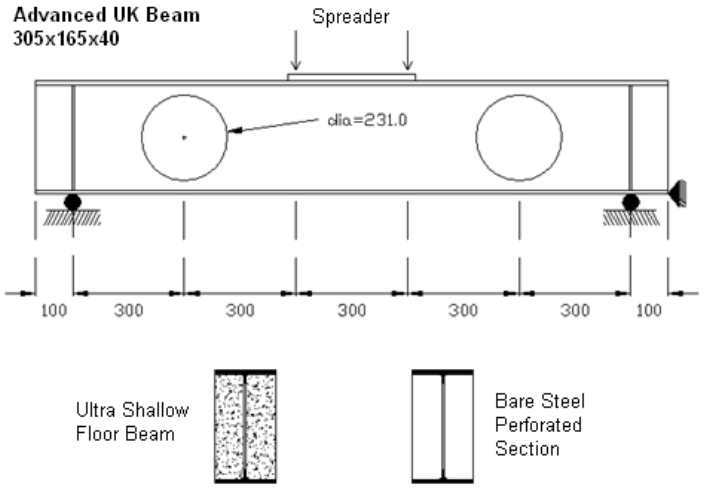

Figure 2. Specimen (all dimensions are in mm).

2 EXPERIMENTAL STUDY

2.1 *Test specimens and loading arrangement*

All material and specimen tests are conducted in the Engineering Department laboratories at City University. A test configuration was chosen to cover the large range of thin web beams mostly utilised as floor beams. The steel section adopted was the UB305x165x40 of steel grade S275, with a web opening diameter, d_o, equal to 0.76 times the beam section depth. The distance between the openings and the support centre-line is equal to $1.3d_o$ and the beam is symmetrical about the mid-span centre-line. To ensure adequate load distribution from supports and applied load, bearing stiffeners are utilized as well as a spreader plate at mid-span of the compression flange.

Three composite beams with similar concrete strength at 14 days of curing, and one with similar strength at 52 days of curing (lower grade concrete) were tested. The results of composite beams were directly compared with that of the bare steel beam. In order for the results of these tests to be included in the design procedures, a lower bound was required and the concrete mix was designed to have a strength no greater than 35MPa at the test date. The actual strengths are between 25 to 30MPa.

The four-point bending load arrangement, with simply supported ends, results in a pure bending moment distribution over the mid-span of the beams. The load was applied through two hydraulic jacks and a spreader plate. The applied load and bending moments were obtained from the load cells connected to the jacks. The rig set-up and test arrangement is shown in Figure 3.

To measure vertical deflection, three displacement transducers were placed under the tension steel flange and aligned with the edge of the hole. Two dial gauges were placed at the high moment side of each web opening; (Dial Gauge 1 and 3) and one dial gauge at the mid-span of the test beams (Dial Gauge 2).

For the bare steel beam only, strain gauges were located on both sides of the web at both web openings. The gauges were used to measure the compressive and tensile surface strains of the beams in the vicinity of the web openings and to determine the areas of yielding and local buckling. (Larnach & Park 1964)

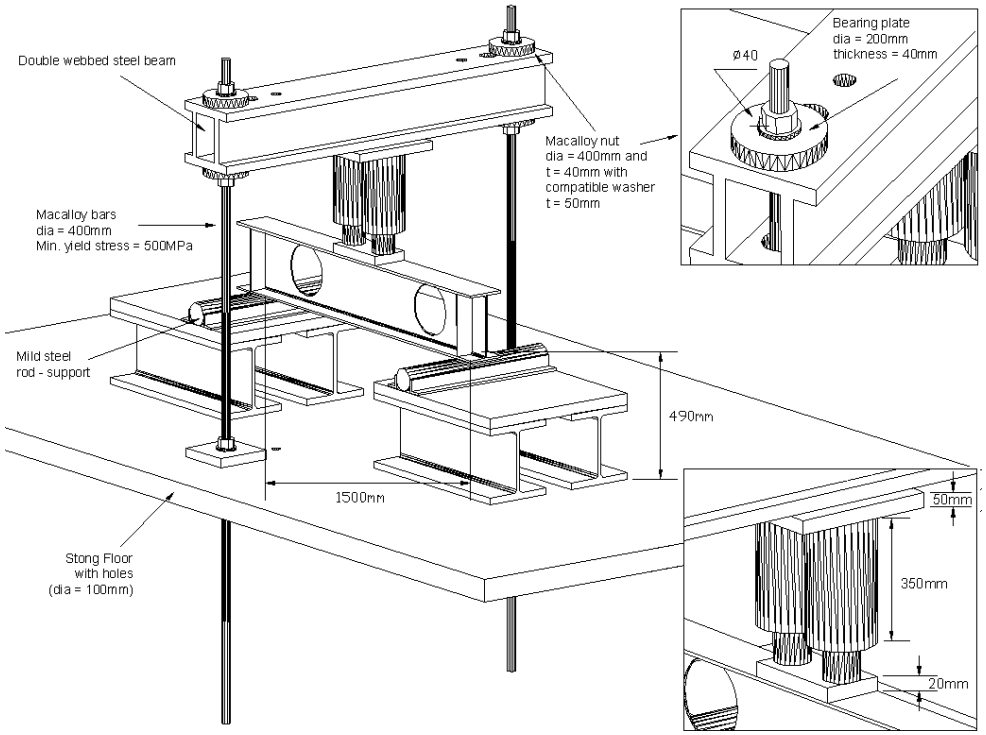

Figure 3. Experimental rig arrangement.

2.2 *Material properties*

The material properties steel coupon tensile tests (Allan 1997) and concrete cube compressive tests (Lydon 1982) are summarised in Table 1. Averaged values are presented. Cube tests were carried out at 3, 7 and 14 days following the methodology in BS EN 197. (BS EN 197: Part 1: 2000). Table 1 contains the concrete strength at the time of testing (14 days). Specimen 4 with a lower concrete strength was tested at 52 days.

Table 1. Averaged material properties for steel and concrete

Specimen	Average Yield Stress of Steel, f_y, (MPa)		14-Day Compressive Strength of Concrete, f_{cu}, (MPa)
	Web	Flange	
USFB No.1	299.0	337.5	27.907
USFB No.2	299.0	337.5	26.765
USFB No.3	299.0	337.5	25.331
USFB No.4	299.0	337.5	25.619 (@ 52-Day)

2.3 *Test procedure*

After a preloading stage, the load was applied in steps at a low displacement rate, and held at each step to allow load relaxation. All test specimens were loaded past the ultimate load to obtain a significant part of the post-failure curve. Concrete crack patterns were recorded throughout the tests. Initially the beams were loaded with approximately 10kN and the dial gauges zeroed. The load was then released and reloaded gradually in 20kN increments and 40 to 50kN increments for the bare steel beam and USFBs, respectively. The loading increments were reduced after first yielding to approximately 10kN and 20 to 30kN for the bare steel beam and USFBs, respectively; up to the point of the beams' ultimate load carrying capacity and then a further reduction of the increment to approximately 5 to 10kN per step in the post-elastic region. The general test-procedure is summarised in the following four steps as following: i) preloading, ii) monotonic loading, iii) gradually loading and relaxation and iv) unloading.

3 EXPERIMENTAL RESUTLS

3.1 *Bare steel beam*

The load-deflection curve for the bare steel perforated section with circular web openings for each of the three dial gauges is shown in Figure 3. Up to the level of 176.2kN, which is the 64.2% of the ultimate carrying capacity of the beam, linear behaviour is observed. As it is shown in Figure 4 at around 256kN, local buckling at compression points of the holes' edge, as well as yielding of the compression flange above the web openings, takes place. This is due to the high Vierendeel bending forces in the section. The ultimate loading carrying capacity is 274.4kN, where only Dial Gauges 1 and 3 record measurements. Dial Gauge 2 located at the mid-span of the beam became de-attached following high deformations. The overall flexural failure mode and the locally distorted web and flanges of the steel section as well as the elongation of the circular web opening shape are illustrated in Figure 5.

In Figure 3 the load P_y indicates the experimental value when first yielding at the edges of the circular holes occurs. Furthermore, the yield load P_y, indicates that both the web and the flange sections will yield completely. The buckling load P_{cr} of the web and the flanges is determined from the records of the deflection gauges underneath the tension flange located at the high moment side of each web opening. The yield load P_y is smaller than P_{cr} and P_{max} because the edges of the circular holes carry additional moments by Vierendeel action and longitudinal shear forces (full plastic hinge formation), in addition to the normal bending moment and vertical shear force. Therefore, it appears that this local yielding of the edges is directly related to the ultimate strength of the beam.

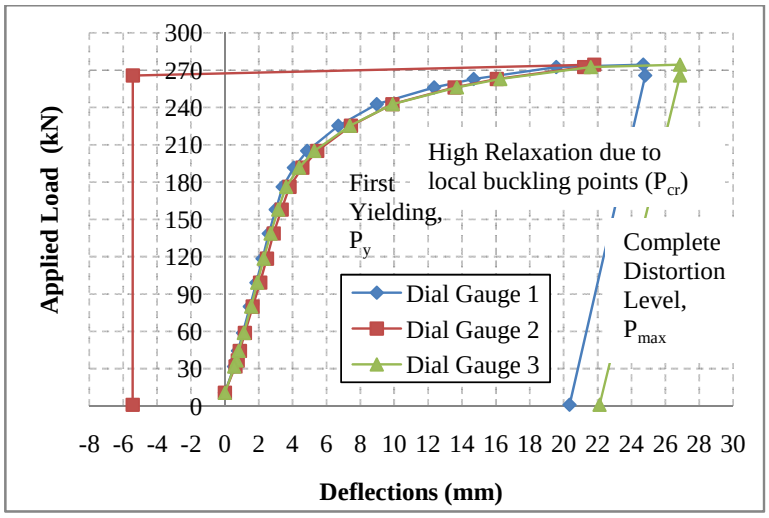

Figure 4: Failure Bare Steel Perforated Section Beam in Flexure.

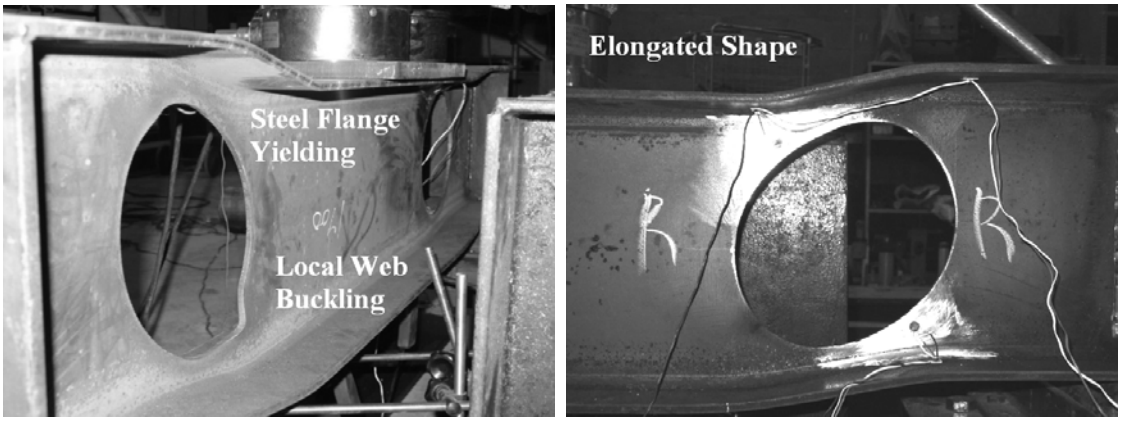

Figure 5. Local highly distorted web - flanges and web opening elongated shape.

3.2 *Ultra Shallow Floor Beam (USFB)*

3.2.1 *Load vs. Deflection relationships*

The results of the tests are shown in Figure 6. Approximately linear behaviour is observed in all tests until around 500kN, which is approximately 89% of the ultimate load carrying capacity of the composite beams. The ultimate load was attained around 600kN after which unloading occurred. Initial failure occurred around 75%, 67%, 70% and 71% of the maximum load for USFB No.1, USFB No.2, USFB No.3 and USFB No.4, respectively. The deflection values are found to be higher in USFB No.1 where the post-failure behaviour is better than the other tests, where a significant drop of load occurred directly after reaching the ultimate load capacity. This was probably due to the large cracks that occurred in the vicinity of the openings, and their rapid propagation.

3.2.2 *Failure mechanism*

Initially, diagonal tension cracks occurred in the early stages, around 250 to 300kN. When these cracks extend fully between the load spreader and support, a rupture plane forms. This can be seen in Figures 7 to 10. Also, at this point, some vertical flexural cracks propagated in the region of constant moment, starting from the tension face and extending upwards to the mid-depth of the beam. At approximately 550kN, plasticity commences as the flexural cracks move upwards. Eventually, crushing of the concrete occurs in the constant moment region. Full development of diagonal cracks ensues at this point in all composite beams where the reduction of the load capacity and beam stiff-

ness begins. The principle diagonal cracks in all three tests were not in identical positions and there was a slight variation in the angles of the cracks. However, these angles of the principal diagonal cracks and hence the failure mechanisms are similar. It should be noted that all major cracks and final concrete failure developed at one side of the beam. After this, the plastic behaviour of the composite sections is mainly due to the steel beam's low stiffness and high deformation. Around 600kN the ultimate load carrying capacity is achieved, and the post-failure curve shows a considerable drop in the load carrying capacity. This is accompanied by large cracks in the vicinity of the web openings. As mentioned previously, the strength of perforated beams is reduced due to inherent stress concentration at the 'corners' of the web openings (known as plastic hinges). Following the formation of the large cracks, there is some residual strength in the concrete and the load carrying capacity is somewhat higher than that of the bare steel beam.

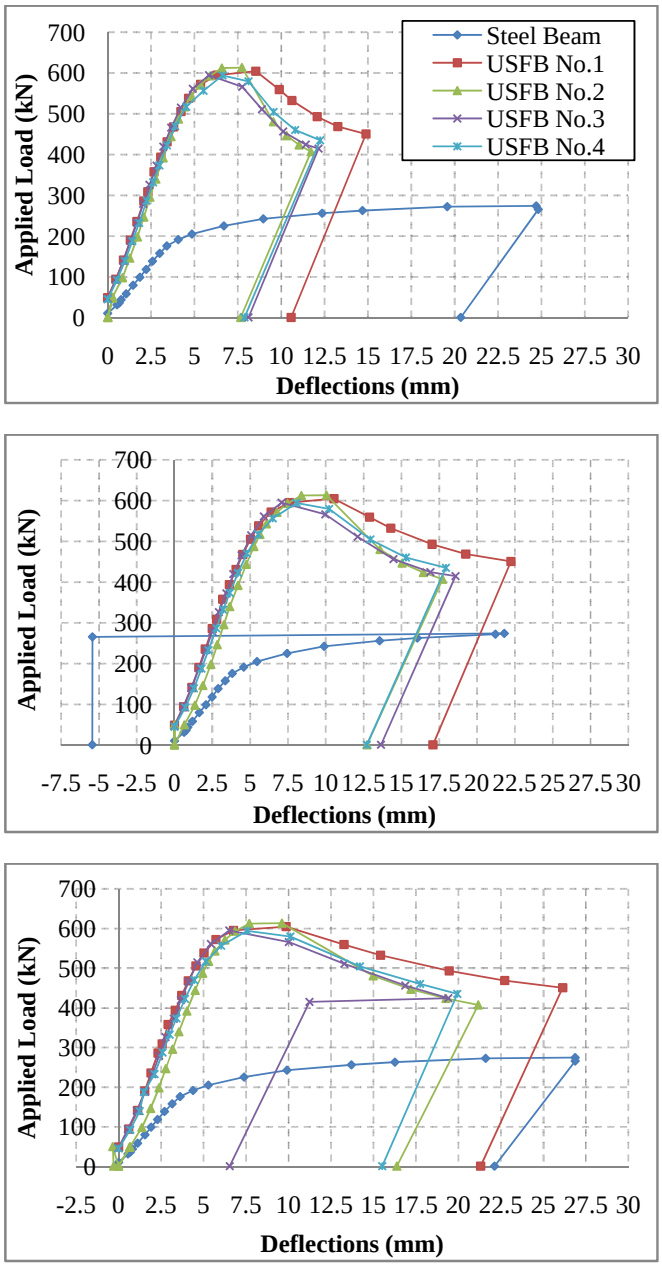

Figure 6. Load vs. Deflection curves for Bare Steel and USFBs for left, middle and right dial gauges.

3.2.3 *Principal diagonal crack angles*

The angles of principal diagonal tension cracks recorded in the tests varied slightly. The angles formed to the left and right web opening were also different. Table 2 shows the angles (±2 degrees) of the principal diagonal tension cracks that were evaluated during the first part of the tests. It can be seen in Figures 7 to 10 that cracks were generated at the position of the web openings, where the steel experiences maximum stresses.

Table 2. Angles of the Principal Diagonal Tension Cracks

Beam	USFB No.1		USFB No.2		USFB No.3		USFB No.4	
Web Opening	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
Approximate Evaluations - Angles (degrees)	33	25	33	29	37	32	33	31

Figure 7. USFB No.1 at Failure point.

Figure 8. USFB No.2 at Failure point.

Figure 9. USFB No.3 at Failure point.

Figure 10. USFB No.4 at Failure point.

4 CONCLUSIONS

The behaviour of all of the composite beams in the test series was similar and the results are therefore somewhat conclusive. The following conclusions can be drawn from this study:

- All four composite Ultra Shallow Floor Beams (USFBs) showed similar behaviour in terms of failure mode configuration, stiffness and ultimate loading carrying capacity.
- Due the concrete in-fill, the ultimate vertical load carrying capacity of the USFBs is double the capacity of the bare steel beam.
- The failure mode of the non-composite beam changes when there is a concrete infill between the flanges. Following the formation of the large cracks, there is some residual strength in the concrete preventing local buckling and the load carrying capacity is somewhat higher than that of the bare steel beam.

- In composite beams, the concrete fails first before any significant distortion of steel web occurs.
- The ultimate load carrying capacity of the composite beams is dependent upon its strength but appears to be relatively independent of the concrete quality.
- For the composite beams, there is a significant and rapid drop in load after failure but the post-failure loads were above those for the plain steel beam.
- The four USFBs presented slightly different angles of cracking in the vicinity of the web openings. For the weaker concrete, cracks occurred at an earlier stage of loading.

The results from this study have been incorporated in the design software for Ultra Shallow Floor Beams (USFB AutoMate v1.0).

5 AKNOWLEDGEMENTS

The authors would like to thank the Westok group for the supply of the steel perforated specimens and the Steel Construction Institute (SCI) for the approval of the experimental structural arrangement and geometrical configurations of the specimens.

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