Influence of concrete slabs on lateral torsional buckling of steel beams

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ABSTRACT: The use of pre-cast concrete floor slabs in steel framed structures is quite common. In the design of the steel beams, the lateral restraining effect of the pre-cast concrete slab is normally safely neglected. However, the concrete slab will provide some horizontal restraint, even without special provisions such as dowels being present. It may even be that the restraint provided by the floor slab prevents lateral torsional buckling. To investigate the restraining effect of a concrete slab on the top flange of a steel beam subject to lateral torsional buckling, two experimental load tests were performed. The first test is a so called reference test where a steel beam with lateral restraints at the supports only (fork conditions), was loaded in four point bending. In a second test, a single 1.2 m wide non-connected concrete slab was placed on a strip of rubber at mid span of the steel beam with the same support conditions. The tests were carried out on 7.2 m long IPE240, S235 beams subject to identical loading conditions. The test results have been compared with results obtained from Finite Element simulations and theoretical analyses. It was observed that the non-connected pre-cast concrete slab, placed on top of the steel beam, performed as a lateral support against lateral torsional buckling such that the beam almost reached its full plastic mechanism capacity. This preliminary study shows promising results. Further research is planned to quantify the restraining effect of floor slabs on the lateral torsional buckling behaviour of steel floor beams.

1 INTRODUCTION

The use of pre-cast concrete floor slabs in steel framed structures is quite common. Floor slabs can be placed on top of steel beams to form a floor structure. In the design of the steel beams, the lateral restraining effect of the pre-cast concrete slab is normally neglected. This is a safe approach. If lateral torsional buckling is governing the design and the design load cannot be carried, special provisions such as intermediate lateral supports can be applied to sufficiently restrain the steel beams against lateral torsional buckling. In reality, the concrete slab will provide some horizontal restraint, even when no special provisions are taken. Two restraining influences are distinguished:

- the lateral displacement of the steel beam may be (partly) prevented because of friction between floor slab and steel beam
- the rotation of the top flange of the steel beam may be (partly) prevented since the load is shifted to the flange tip in case of rotation of the cross-section.

It may even be that the floor slab prevents lateral torsional buckling to occur.

To investigate the restraining effect against lateral torsional buckling of a pre-cast concrete slab on the top flange of a steel beam subject to bending, two tests were performed. The first test is a so called reference test where a steel beam with lateral restraints at the supports only (fork conditions), was loaded in four point bending. In a second test, a single 1.2 m wide pre-cast concrete slab was placed on a 20 mm thick, 10 cm wide strip of rubber at mid span of the steel beam with the same support conditions. The tests were carried out on 7.2 m long IPE240, S235 beams subject to the same loading conditions.

The test results have been simulated by making use of the Finite Element Method (FEM) and the load-deflection behaviour and ultimate loads have been compared.

Also, the ultimate loads of the tests have been compared with results obtained from theoretical analyses.

2 EXPERIMENTS

Normally, a floor slab is present over the complete length of a steel beam and the beams may be continuous. However, a situation like that is complex to test in the laboratory. Therefore, it was decided to place a single 1.2 m wide pre-cast concrete slab in the centre on the top flange of a beam with torsionally restrained fork end supports. Between steel beam and concrete slab, a 20 mm thick 10 cm wide rubber strip was placed, which is commonly used for noise and vibration isolation purposes in e.g. cinema structures.

Two different four point bending tests were carried out: one reference test for lateral torsional buckling without the concrete slab being present and one similar test with the concrete slab being present. The load is applied by two separate jacks since the deflection of the beam is expected to result in a concentration of force transfer between concrete and steel near both ends of the concrete slab. The two tests are shown schematically in Figure 1.

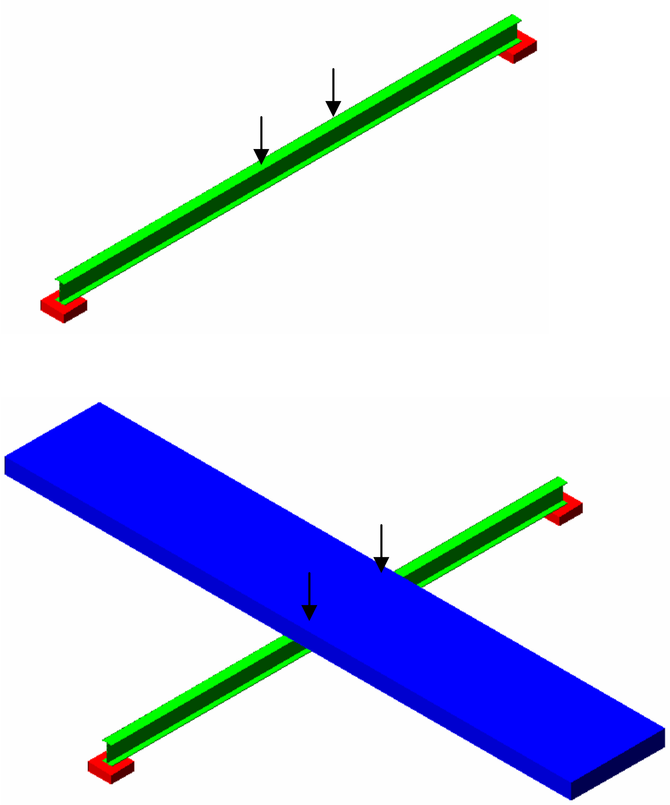


Figure 1. Lateral torsional buckling test 1 without floor slab (top) and test 2 with floor slab (bottom).

In both tests, the span was 7.2 m (physical length of specimens 7.5 m), fork conditions were established at the simple supports and IPE240 sections in S235 were used. The actual mean values of the yield stress were determined to be $f_y = 308$ N/mm2 for test 1 without concrete slab and $f_y = 306$ N/mm2 for test 2.

2.1 *Test set-up*

For test 1 without concrete slab, the test was carried out by applying the two point loads in tension, testing the beam in upside down position. The point loads had to be vertical throughout the test, without rotating with the beam in case of lateral torsional buckling. Therefore, a 7.8 m high frame (Figure 2) was built to get sufficient height keeping the point loads as vertical as possible. Load introduction frames were built around the beam, to apply the load to the bottom flange of the beam.

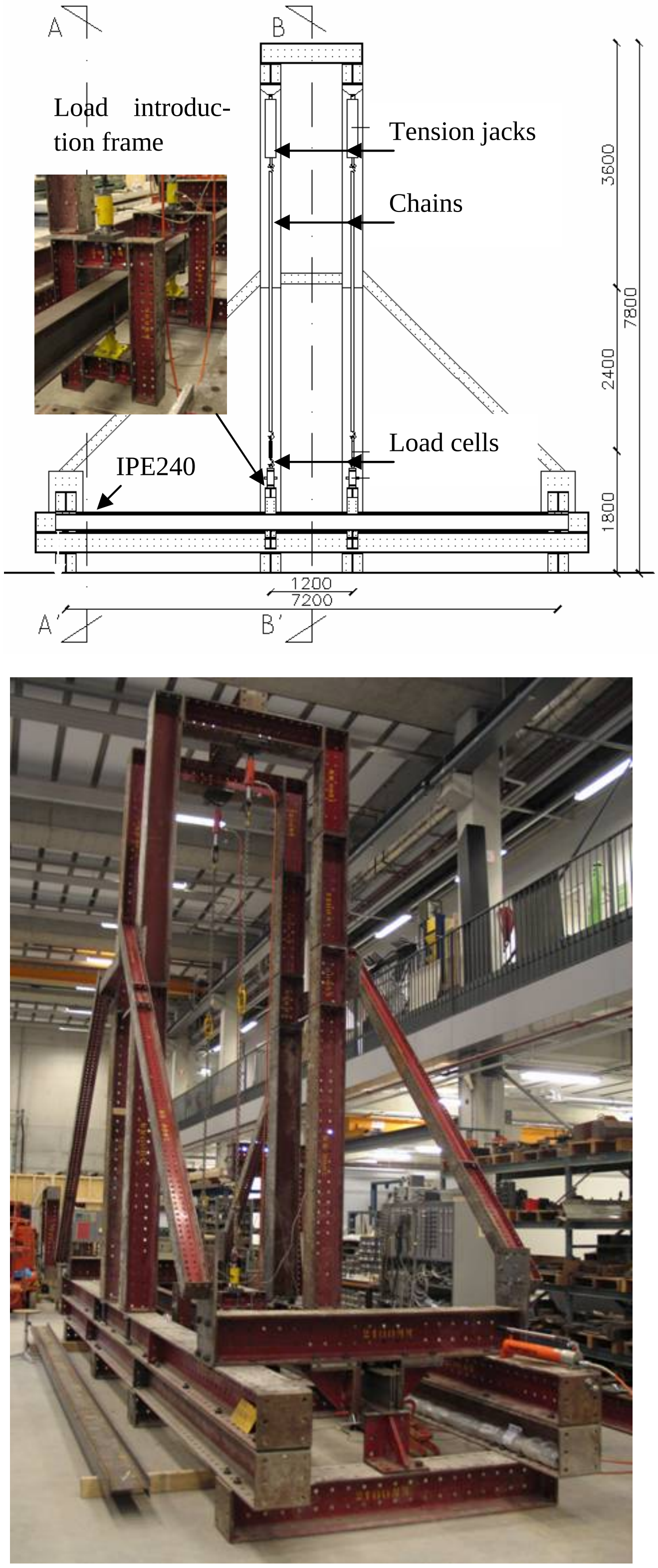
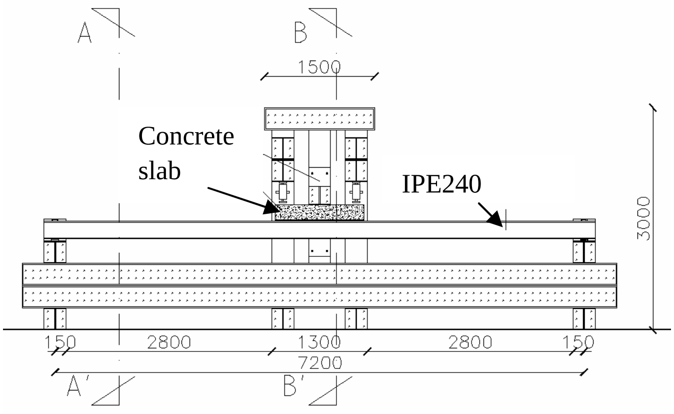
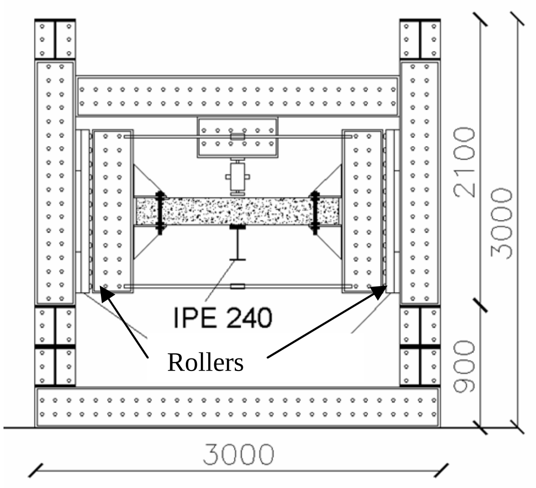


Figure 2. Test set-up for test 1 without concrete slab.

For test 2 with concrete slab, it turned out to be easier to apply the point loads in compression and test the beam in normal position (Figure 3). Here, the concrete slab (concrete B35, 1200 mm wide,





Cross-section B-B

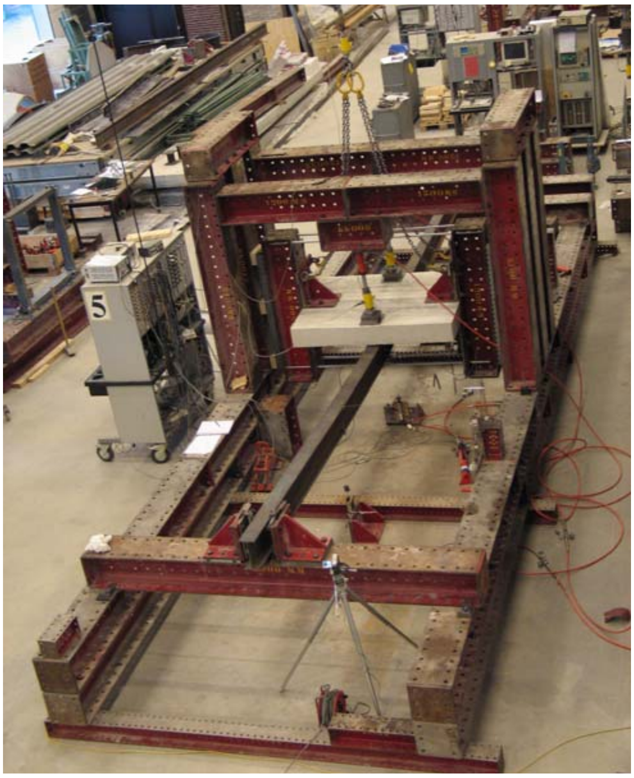


Figure 3. Test set-up for test 2 with concrete slab.

1500 mm long and 200 mm thick) was pushed against the beam via a rubber strip (1200 mm long, 100 mm wide and 20 mm thick). In this test it was important that the concrete slab does not rotate. Using a frame around the concrete slab, the slab was

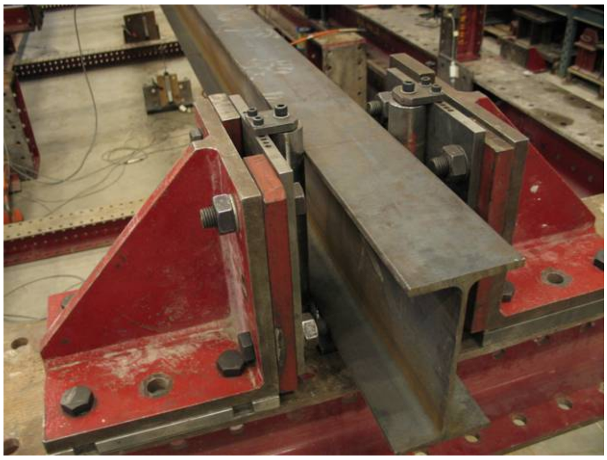


Figure 4. Support with fork conditions.

kept in a horizontal position making use of vertical rollers. The end supports in both tests were identical. The beam was supported by a roller bearing. In both cases fork conditions were established as indicated in Figure 4.

2.2 *Test results*

Horizontal and vertical displacements were measured at mid span and at quarter span positions. Also, strains were measured at mid span.

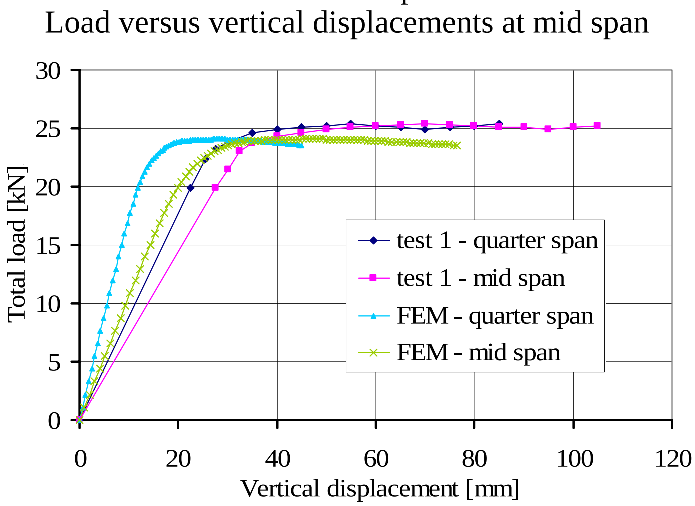


Figure 5. Load versus vertical deflection at mid span and at quarter span position – test 1.

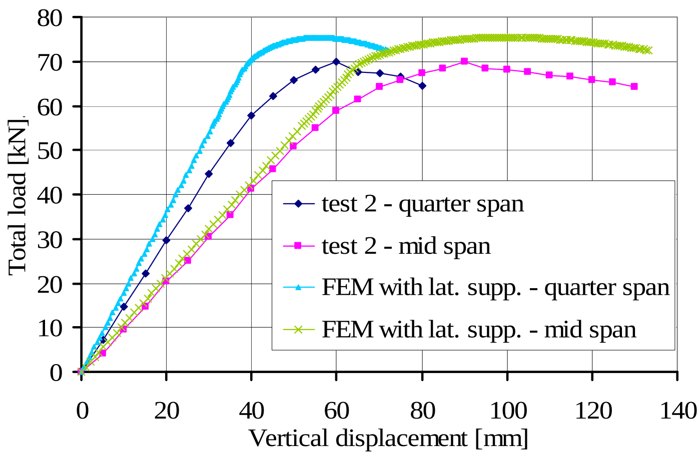


Figure 6. Load versus vertical deflection at mid span and at quarter span position – test 2.

and at quarter span position are shown in Figures 5 and 6 for test 1 and 2 respectively, together with Finite Element results.

In Figures 7 and 8, the load versus horizontal displacements at mid span and at quarter span positions are shown for test 1 and 2 respectively, together with Finite Element results.

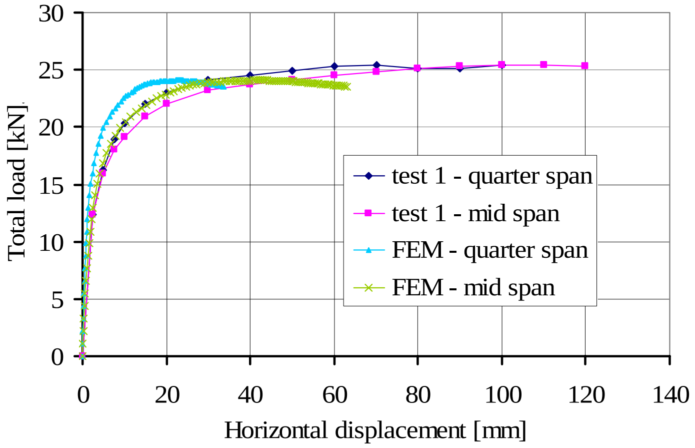


Figure 7. Load versus horizontal deflection at mid span and at quarter span position – test 1.

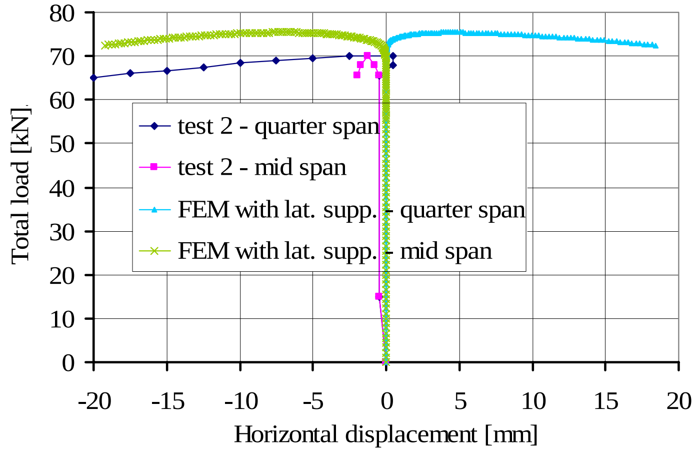


Figure 8. Load versus horizontal deflection at mid span and at quarter span position – test 2.

In Figure 9 the load versus strains at mid span are shown. Strains were measured at the inside of the flanges on both sides of the web: 4 locations in total.

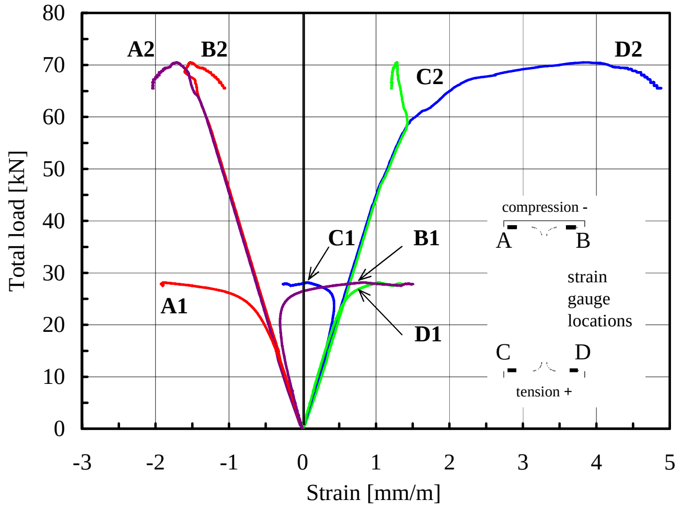


Figure 9. Load versus strain at mid span.

2.3 *Discussion of test results*

The ultimate total load of test 1 without concrete slab was 28.0 kN. The dead load of the load introduction frames is 2.6 kN so the ultimate total load is in fact $F_t = 25.4$ kN. The beam failed by lateral torsional buckling as was observed in the test and can be concluded from Figures 7 and 9. In Figure 7 it can be seen that the beam moves sideways and in Figure 9 it can be seen that the strains change from tension to compression and vice versa which corresponds to the fact that the cross-section of the beam is rotating as well.

The ultimate load of test 2 with concrete slab was $F_t = 70.0$ kN. In this case lateral torsional buckling was not observed. The strains do not change sign as can be seen in Figure 9. At mid span position the beam did not displace much (Figure 8) but the beam displaced more at quarter span positions showing an S-curve. The beam displaced sideways after reaching the ultimate load.

3 FINITE ELEMENT SIMULATIONS

The tests are simulated using the Finite Element Method with the computer program DIANA (Witte & Schreppers 2005) for better understanding of the behaviour observed in the tests.

3.1 *Simulation of test 1*

The Finite Element model is built up using 8-node shell elements CQ40S (Figures 10 and 11). Since these elements cannot model the fillet between flange and web, additional 2-node beam elements LE12BE are introduced to make up for the cross-sectional area and the second moment of area. To compensate for the St. Venant torsional constant, additional 2-node torsional spring elements SP2RO are introduced at the intersection of web and flange. The model is made with the same orientation as the test; the chains in the test were simulated by 2-node truss elements L6TRU. The fork conditions at the supports are modelled as indicated in Figure 11.

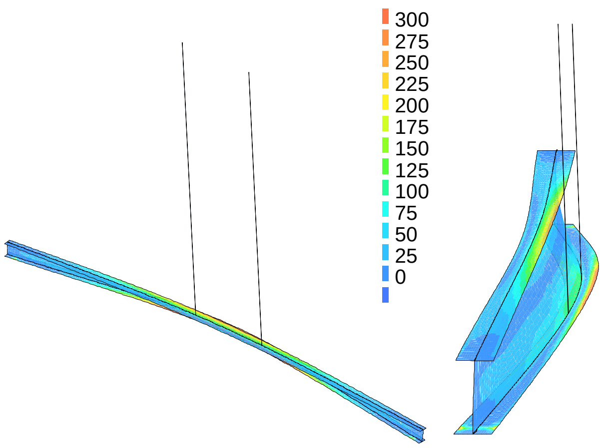


Figure 10. Deformed Finite Element model for test 1 at ultimate load indicating Von Mises stresses (N/mm^2).

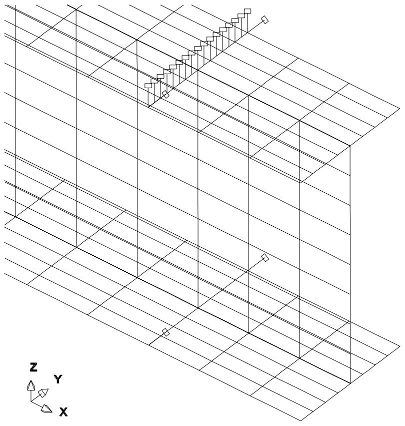


Figure 11. Support with fork conditions.

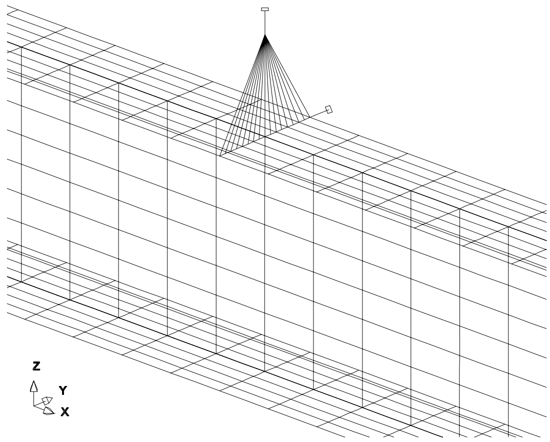


Figure 12. Modelling of load introduction for test 2.

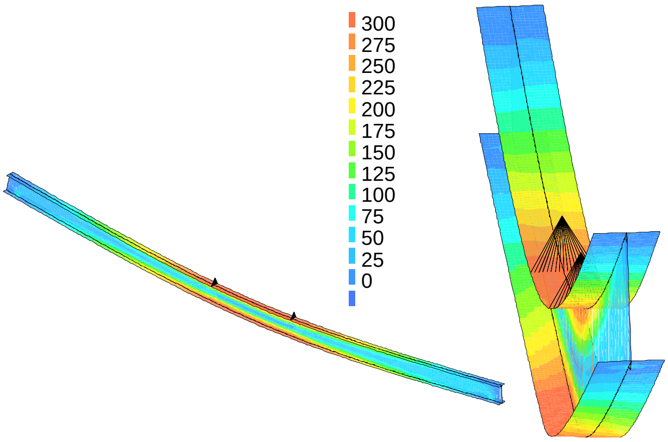


Figure 13. Deformed Finite Element model for test 2 at ultimate load indicating Von Mises stresses (N/mm^2).

The simulation is carried out as a geometrical and material non-linear analysis on a beam with imperfections (GMNIA). Since measured imperfections are not available, the Euler buckling mode is used as imperfection mode, scaled in such a way that the maximum imperfection is $\ell/1000$, where ℓ is the span length. A bilinear stress-strain curve is used to model the material characteristics.

The ultimate total load obtained with this calculation is $F_{FEM} = 24.1$ kN. In Figure 10 it can be seen that the failure mode is lateral torsional buckling. Load versus displacements at mid span and at quarter span position are shown in the Figures 5 (vertical displacements) and 7 (horizontal displacements) and compared with test results. The Finite Element model behaves stiffer than the experiment (Figure 5) but in general, there is a reasonable agreement between FEM and experiment.

3.2 *Simulation of test 2*

The Finite Element model to simulate test 2 is built up in the same way as for test 1. The points of load introduction are assumed to be at the edges of the concrete slab because of the relatively large stiffness of the concrete slab compared to the beam stiffness. When the cross-section of the beam rotates, the point of load introduction will shift towards the flange tip. This is simulated by adding spring elements SP2TR to the top flange, which have a high stiffness in compression and almost no stiffness in tension (Figure 12). The springs act in vertical direction.

In Figure 12, a lateral support at the point of load introduction is shown as well. In case this lateral support is omitted, a lower bound for the real behaviour is obtained with a GMNIA calculation. For this case the ultimate total load was calculated to be $F_{FEM,lb} = 57.7$ kN.

In case the lateral support at the point of load introduction is present, as in Figure 12, an upper bound for the actual behaviour is obtained with a GMNIA calculation. Then, the ultimate total load becomes $F_{FEM,ub} = 75.4$ kN. For this situation, the deformations and Von Mises stresses at ultimate load are shown in Figure 13. It can be observed that lateral torsional buckling does not occur.

Load versus displacements at mid span and at quarter span position are shown in the Figures 6 (vertical displacements) and 8 (horizontal displacements). There is a reasonable agreement between Finite Element and experimental results.

4 THEORETICAL ANALYSES

The ultimate load is calculated in two ways, using the design rules of Eurocode 3 (EN1993-1-1 2006) for lateral torsional buckling and using plastic (mechanism) theory.

4.1 *Lateral torsional buckling theory*

The lateral torsional buckling ultimate load is calculated with the standard procedure of EN1993-1-1, clause 6.3.2.1 and 6.3.2.2 (EN1993-1-1 2006). The calculations given below are for test 1 without concrete slab. The results for test 2 with concrete slab are given in brackets. To calculate the non-dimensional slenderness, the elastic critical moment is required. The elastic critical total load was determined using the FEM: $F_{cr} = 24.4\,(140.8)$ kN. For test 2 it was assumed that the concrete slab forms a lateral support at the points of load introduction (Figure 12). The elastic critical moment is then

$M_{cr} = 3 \cdot 24.4/2 = 36.6\,(211.2)$ kNm. The resistance for bending (plastic moment capacity) is $M_{pl} = 308 \cdot 366 \cdot 10^{-3} = 112.9\,(112.2)$ kNm. Now, the non-dimensional slenderness can be calculated: $\bar{\lambda}_{LT} = \sqrt{112.9/36.6} = 1.756\,(0.729)$. With $h/b = 240/120 = 2 \leq 2$ it follows that lateral torsional buckling curve "a" is valid. Then $\Phi_{LT} = 2.205\,(0.821)$ and the reduction factor $\chi_{LT} = 0.283\,(0.834)$. Now, the ultimate lateral torsional buckling moment becomes: $M_b = 0.283 \cdot 112.9 = 32.0\,(93.6)$ kNm. Then, the lateral torsional buckling ultimate load becomes: $F_b = 2 \cdot 32.0/3 = 21.3\,(62.4)$ kN.

4.2 *Plastic theory*

In case it is assumed that lateral torsional buckling is completely prevented, the ultimate plastic load can be calculated using plastic mechanism theory (Figure 14). The internal energy dissipated in the plastic hinges is:

$$A_i = 2 \cdot M_{pl} \cdot \phi \tag{1}$$

The external energy due to loading is:

$$A_e = 2 \cdot \frac{1}{2} F \cdot \frac{\ell}{2.4} \cdot \phi \tag{2}$$

Setting eqn. (1) equal to eqn. (2) gives:

$$2 \cdot M_{pl} \cdot \varphi = 2 \cdot \frac{1}{2} F \cdot \frac{\ell}{2.4} \cdot \phi \tag{3}$$

So the ultimate plastic load is:

$$F_p = \frac{4.8 M_{pl}}{\ell} \tag{4}$$

Eqn. (4) yields $F_p = 75.3\,(75.5)$ kN.

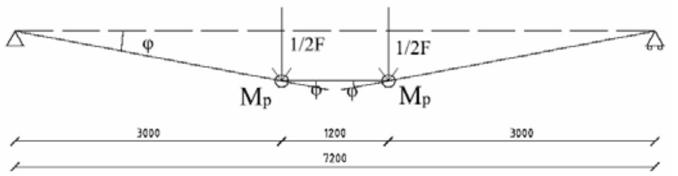


Figure 14. Plastic mechanism.

5 DISCUSSION

The ultimate total loads are summarised in table 1. Also, the deviations of FEM and theoretical results when compared with test results are given as a percentage.

For the case without concrete slab, the FEM predicts the experimental ultimate load well (5%). The theoretical lateral torsional buckling value is closer (16%) to the experimental ultimate load than the value obtained with plastic mechanism theory (-196%).

Table 1. Ultimate total loads (kN)

	Experiment	FEM	Theory	
			LTB	PMT
Without concrete slab	25.4	24.1 5%	21.3 16%	75.3 -196%
With concrete slab	70.0	57.7 (lb) 18%	62.4 11%	75.5 -8%
		75.4 (ub) -8%		

LTB=Lateral Torsional Buckling, PMT=Plastic Mechanism Theory, FEM= Finite Element Method, lb=lower bound, ub=upper bound

For the case with concrete slab, the FEM ultimate loads are upper and lower bounds, the upper bound being closer to the experimental ultimate load (-8%). The theoretical buckling load obtained with the plastic mechanism theory is closer (-8%) to the experimental ultimate load than the value obtained with lateral torsional buckling theory (11%). The upper bound of the ultimate load obtained with the FEM is confirmed by plastic mechanism theory.

These results indicate that the concrete slab is almost able to completely restrain the beam against lateral torsional buckling such that the beam nearly reaches its plastic mechanism capacity.

6 CONCLUSIONS

It was observed that the non-connected pre-cast concrete slab, placed on top of the steel beam, performed as a lateral support against lateral torsional buckling such that the beam almost reached its full plastic mechanism capacity. This preliminary study shows promising results. Further research is planned to quantify the restraining effect of floor slabs on the lateral torsional buckling behaviour of steel floor beams.

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