NOVEL STEEL YIELDING SHEAR CONNECTOR FOR DEMOUNTABLE PRECAST COMPOSITE FLOORS

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1. ABSTRACT

Η παραγωγή χάλυβα και σκυροδέματος ευθύνεται για το 15% της παγκόσμιας παραγωγής διοξειδίου του άνθρακα, ενώ ο σύγχρονος τρόπος κατεδάφισης των κτιρίων οδηγεί σε ένα μεγάλο αριθμό αποβλήτων οικοδομής. Ο συμβατικός τρόπος κατασκευής των σύμμικτων δοκών απαιτεί συγκόλληση των διατμητικών συνδέσμων στο άνω πέλμα της δοκού, καθιστώντας αδύνατη την αποσυναρμολόγηση της κατασκευής και την επαναχρησιμοποίηση των στοιχείων. Η παρούσα έρευνα αφορά μία καινοτόμο σύνδεση μεταξύ προκατασκευασμένων πλακών και μεταλλικής δοκού, η οποία περιλαμβάνει μία μεταλλική συσκευή ως διατμητικό σύνδεσμο η οποία βιδώνεται πάνω στη μεταλλική δοκό. Μια σειρά από πειράματα διεξήχθησαν στοχεύοντας αφενός στον προσδιορισμό της σχέσης δύναμης-ολίσθησης στη διεπιφάνεια και αφετέρου στην εκτίμηση της διαδικασίας αποσυναρμολόγησης των πειραματικών δοκιμίων. Τα πειράματα έδειξαν: 1) αυξημένη αντοχή και πλαστιμότητα για τον καινοτόμο διατμητικό σύνδεσμο έναντι του συμβατικού; και 2) πλήρη επαναχρησιμοποίηση όλων των δομικών μελών των δοκιμίων εκτός από το διατμητικό σύνδεσμο. Η πρόβλεψη της αντοχής διαρροής του συνδέσμου βασίστηκε σε απλές εξισώσεις θεωρίας πλαστικής ανάλυσης.

2. INTRODUCTION

The urgent need for sustainable development in modern societies means that human activities need to drastically reduce carbon dioxide (CO2) emissions, waste, and natural resources consumption. The construction sector plays an important role towards this direction, since the production of new materials is energy intensive and produces pollution, whereas structures are usually demolished at the end of their service life. 'Design for deconstruction' is a recent concept that aims at designing buildings using demountable connections to allow for easy dismantling and reuse of components. Steel concrete composite beams are currently constructed using welded studs embedded in cast in-situ concrete and thus making the decostruction of the beam at least problematic.

A limited number of research works have proposed methods to achieve a demountable shear connection (denoted as DSC) in composite beams. Lam et al. [1] presented pushout tests using threaded headed studs that are bolted (instead of welded) on the steel flange and embedded in in situ concrete slabs. Friction grip bolts in conjunction with solid precast slabs, relying on friction forces to resist the longitudinal shear, were used by Bradford et al. [2]. Allwood et al. [3] conducted three experiments on composite beams with DSC; those tests concerned bolted shear studs embedded in in situ composite slabs. Blind bolts as shear connectors embedded in concrete were proposed by Pathirana et al. [4] with emphasis on strengthening existing beams and composite bridge girders. This paper presents a novel demountable shear connection method to connect steel sections with precast hollow-core slabs. The proposed shear connection mechanism provides resistance to longitudinal shear due to steel yielding, resulting in a ductile force-slip behaviour. The paper presents the experimental evaluation of the proposed shear connection and theoretical predictions based on fundamental mechanics.

3. DESCRIPTION OF THE PROPOSED DEMOUNTABLE CONNECTION AND FUNDAMENTAL MECHANICS

The proposed system is a steel concrete composite beam using hollow-core precast slab units (denoted as HCUs) and a demountable steel yielding shear connection mechanism, denoted as yielding pocket (YP), to provide composite action. *Fig. 1a)* shows a plan view of a steel beam with two HCUs. The HCUs include open cores to place transverse reinforcement for the effective connection between adjacent units. An additional edge cut-out is required through the depth of the HCU at the middle position of the unit's width to accommodate the installation of the YP as indicated in *Fig. 1a)*. The YP is a steel hollow section having an additional plate welded at the bottom and total length equal to the slab's depth. Vertical slits (i.e. elongated holes) are opened on the sides of the YP parallel to the steel beam, i.e. in the direction of the longitudinal shear force, as shown in *Fig. 1b)*. The steel strips which are formed between the vertical slits resist the longitudinal shear force, as will be described later in more detail. Aligned slotted holes are opened on the sides of the YP parallel to the steel beam axis. A rebar passes through the aligned holes and placed in the middle open core of the HCU. This rebar serves to prevent the slab from uplifting and the holes are slotted in order to ensure that this rebar is not involved in the shear resisting mechanism. The YP is fixed on the top flange of the steel section using four high strength bolts. In situ concrete is poured to cover the open cores and the gaps between the YPs and the HCUs. Before pouring the concrete, plastic foam is used to create a 'tooth' in the HCU, and so, to reduce the contact area between the concrete and the YP, as shown in *Fig. 1b)*. In this way, a ductile yielding failure of the YP is promoted instead of a brittle shear failure of the bolts that would occur if the concrete was in full-depth contact with the YP. Thus, the shear resistance is provided by bending of the YP's steel strips and vertical walls that are perpendicular to the direction of the steel beam.

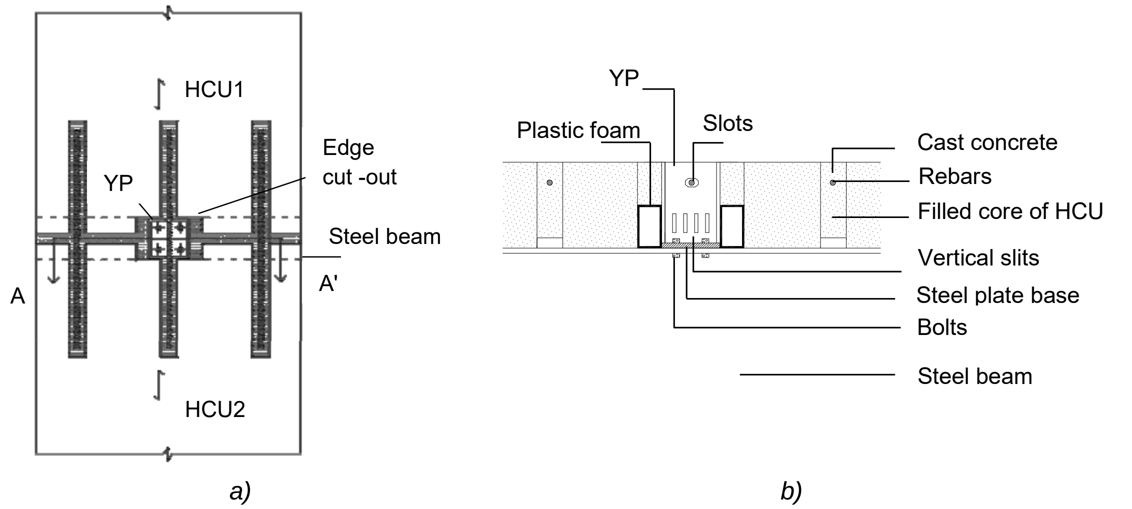


Fig. 1: a) Plan view; b) longitudinal section AA' of the proposed connection

The construction procedure consists of the following steps: a) The HCUs are positioned on the steel beams; b) the YPs are placed on the appropriate positions; c) bolts are used to fix the YPs on the flanges of the steel sections; and d) in situ concrete is poured to fill the open cores with the rebars and the gaps around the YPs. The deconstruction procedure consists of the following steps: a) The concrete in a region around the YP is removed and the middle rebar passing through the YP is cut; b) bolts are removed c) the YPs are pulled out; and d) the HCUs are removed and all components are ready to be reused.

The strength of the YP is the result of two mechanisms: a) the in-plane bending of the steel strips; and b) the bending of the YP's walls transverse to the beam direction. *Fig. 2a)* shows the geometrical characteristics of the YP. The deformed shape of the YP is shown in *Fig. 2b)*. The YP is deformed under displacement imposed by the concrete 'tooth'. The bold line in *Fig. 2* represents the bottom fibre of the concrete 'tooth'.

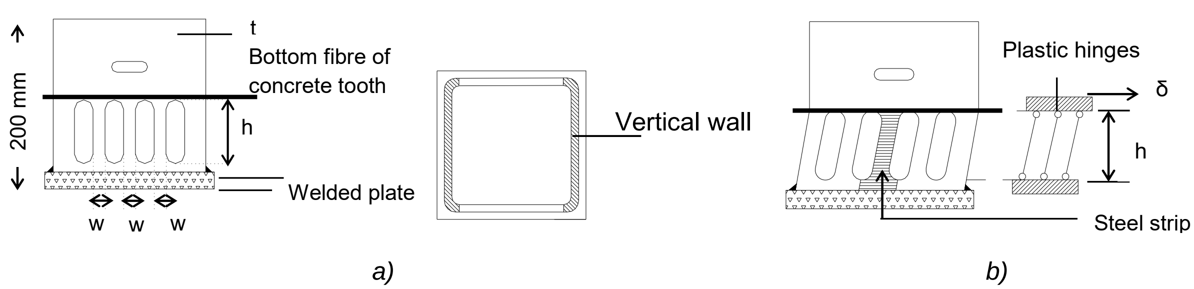


Fig. 2: a) Geometrical characteristics of YP; b) deformed shape of YP

Plastic beam analysis is used to predict the structural behaviour of the YP. Fully fixed boundary conditions are assumed for the end supports of the steel strips and the vertical walls as indicated in *Fig. 2b)*. Plastic hinges are expected to develop at the ends of the steel strips and at the ends of the vertical walls. The plastic moment resistance of a strip $M_{p,strip}$, is calculated as that of a rectangular solid section. Based on plastic analysis principles, the shear strength, $F_{p,\,strips}$, provided by the steel strips is given by:

$$F_{p,srtips} = 2 \cdot \frac{M_{p,strip}}{h} \cdot n \qquad (1)$$

where h is the assumed height of the steel strips, n is the total number of the steel strips, and $M_{p,strip}$ is the plastic moment resistance of a strip.
The plastic moment resistance of one transverse vertical wall, $M_{p,wall}$, is calculated using plastic analysis of the section, shown in *Fig. 3*, taking into account the corners of the YP. The strength provided by the vertical walls, $F_{p,walls}$, is given by:

$$F_{p,walls} = 2 \cdot \frac{2 \cdot M_{p,wall}}{h} \qquad (2)$$

where h is the assumed height of the steel strips, and n is the total number of the steel strips.
Thus, the total shear resistance, F_p, provided by the YP is:

$$F_p = F_{p,strips} + F_{p,walls} \qquad (3)$$

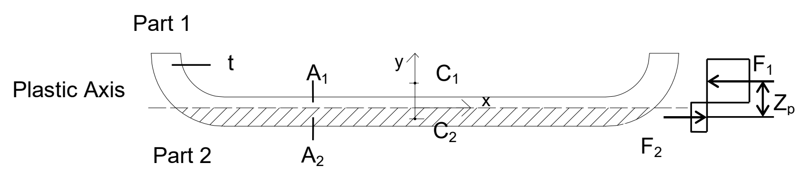


Fig. 3: Plastic analysis of the YP's vertical wall

Capacity design rules are applied in order to ensure that the bolts and the welded plate of the YP remain elastic. The shear strength of the bolts and the bearing resistance of the connected plates at the bolt holes are also checked. The concrete slab is checked in compression.

4. HORIZONTAL PUSH OUT TESTS

A plan view and a longitudinal section of a typical push out specimen are shown in *Fig. 4)* and *Fig. 5)* respectively. The YP is a cold formed hollow section of SHS180X180 tube having a welded plate of 20mm thicknbess at the bottom. The total height of the YP is 200mm equal to the full depth of the HCU. The geometrical characteristics of the YP tested are shown in *Table 1.* Each group includes push out specimens with identical YP geometry. The beam is a universal steel beam of UB533X210X92 section and S355 steel grade. The HCUs are of 1200mm width, 200 mm depth and 800 mm length including the edge cut out. The size of the edge cut out is of 300mm width and 70mm depth, cut through the depth of the slab. Each HCU has five open cores of 500 mm length including the end cores to serve the placement of transverse reinforcement. The fourth core of the HCUs shown in *Fig. 5)* is additionally open. The gap between the two adjacent units is 70 mm. Four high tensile strength bolts of 20 mm diameter and 12.9 steel grade were used to fix the YP on the steel beam. The bolts were tightened using a wrench to apply a 220 N mm torque. Washers and nuts of 8.8 steel grade were used. Rebars of 12 mm diameter were placed in the five open cores. In situ concrete was poured to cover the open cores and the gaps between the YP and the HCUs. The fourth core of the HCUs was casted to avoid premature fracture of the concrete slabs. Plastic foams were used before pouring the concrete to create the concrete 'tooth' and to reduce the contact area between the in situ concrete and the HCUs in the bottom of the HCUs. Material tests were performed to obtain the material properties of the YP and the cast in situ concrete at the day of testing. The material properties of the YP were obtained from standard coupon tests. The coupon specimens were cut from the middle flat part of the YP. The 0.2% proof stress was found 390MPa and 500MPa for the SHS180X180X8 and SHS180X180X10 tube, respectively. A number of concrete cubes of 100x100x100 mm were casted and cured along the push out specimens. The strength of the in-situ concrete of the push out specimens at the day of testing is shown in *Table 1*.

Push out specimens per group	**YP's thickness t [mm]**	**Steel strip's width w [mm]**	**Steel strip's height h [mm]**	**In situ concrete strength f_c [MPa]**	**Number of tests**
SP-1A/SP-1B/SP-1C	10	14	75	50/68/47	3
SP-2A/SP-2B	8	17.33	75	47/40	2
SP-3A/SP-3B	8	13.33	55	47/56	2
SP-4	8	17.33	55	38	1

Table 1: Geometrical characteristics of the YP and in-situ concrete strength of specimens

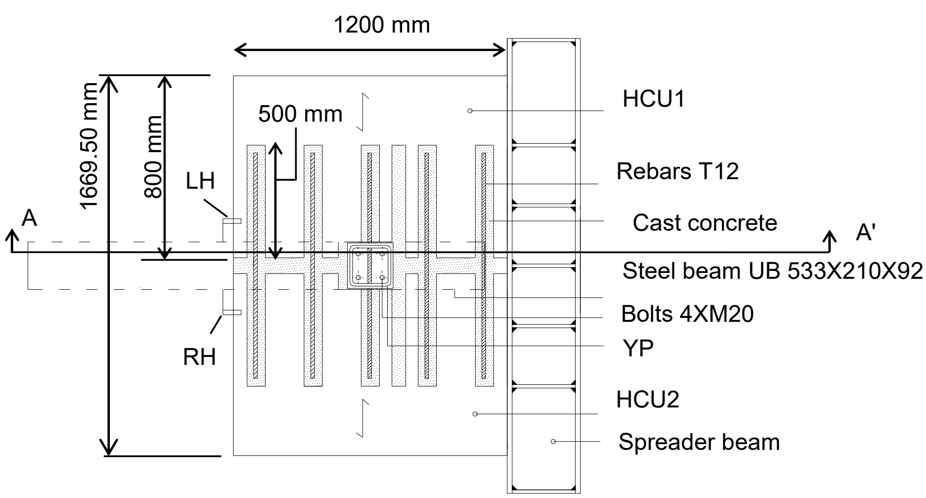


Fig. 4): Typical plan view of a push out specimen

Force control load was initially applied up to 40% of the expected failure load and then cycled 26 times between 5 and 40% of the expected failure load as recommended by EC4 [5]. After the cyclic loading, displacement control load was applied at a constant rate such as failure does not occur in less than 15 minutes. Two LVDTs were used to measure the longitudinal slip between the steel beam and the concrete slabs, one on the left and one on the right side of the specimen. The two LVDTs are denoted as 'LH' and 'RH' in *Fig.4)*.

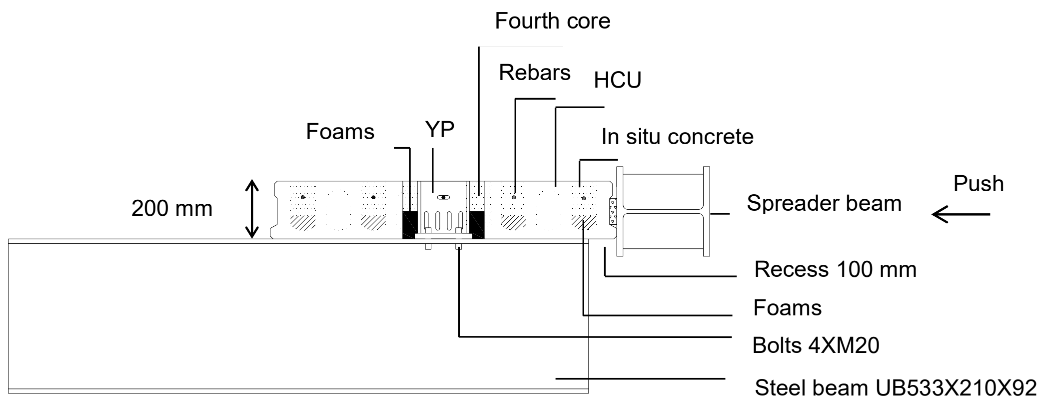


Fig.5): Longitudinal section AA' of a typical push out specimen

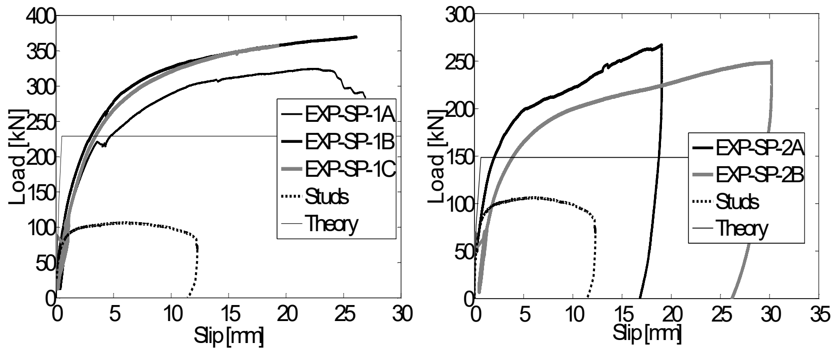
The LVDTs were connected to the steel beam with the aid of magnetic gauge bases. A hydraulic actuator of 1000kN force capacity and 500 mm displacement capacity with attached load cells was used to push the concrete slabs against the steel beam through the spreader beam in the direction shown in *Fig. 5)*. The bottom flange of the steel beam was bolted to the strong floor of the lab. The concrete slabs protrude 100mm from the steel beam to allow the horizontal movement of the spreader beam. Displacement and force were automatically recorded at a frequency of 5Hz.

5. EXPERIMENTAL RESULTS

The experimental results showed that the only damaged member of the connection was the YP and that all the component parts of the connection were reusable at the end of the test apart from the YP. Only the slabs of the push out specimen SP-1A excibited splitting and cracking. The transverse crack propagated from the corners of the YP at a slip of 3.4 mm until the ends of the HCUs through the joined surface of the HCU and in situ concrete. The failure was attributed to poor bonding between the in-situ concrete and the HCUs interface. Deconstruction and reuse were implemented by assembling one push out specimen reusing the structural components of a previous tested one. *Fig.6a)* shows the push out specimen SP-3A which was assembled using all the structural parts of the push out specimen SP-2A apart from the YP. *Fig. 6b)* shows the deformed shape of the YP of the specimen SP-3A at the end of the test. The deformed shape of the YP is typical for all the specimens. *Figs. 7 and 8* show the slip-load curves for the push out specimens tested. Each slip-load curve corresponds to average values obtained from the two LVDTs. The sudden drop in the slip-load curve of the push out specimen SP-1A represents the splitting of the HCUs. The difference in the slip-load curves of the push out specimens SP-2A and SP-2B is attributed to the opening of the corners of the YP of the latter. The slip-load curve of a 19mm diameter headed stud obtained from previously conducted push out tests [6] is superimposed to the slip-load curves. The experimental results show that the demountable shear connection can achieve increased strength and ductility and that the initial stiffness of the proposed connection is comparable to the one of a conventional 19-mm headed shear stud. It is noted that the maximum slips do not correspond to fracture of the YP. The test was discontinued at those slip values as they were excessively high and far beyond the slip expected in a composite beam at the Ultimate Limit State. *Table 2* summarizes the experimental results given together with the prediction of the shear resistance according to *Eqs.(1)-(3)*.

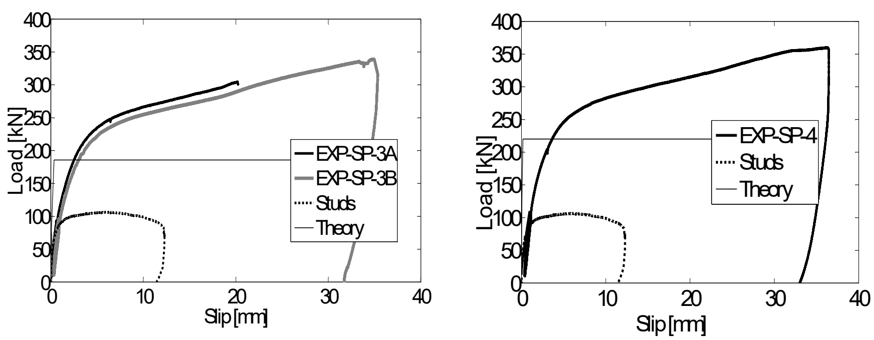
a) b)

Fig.6: a) Specimen SP-3A before castin; b) deformed shape of YP at the end of the test



a) *b)*

Fig.7: Slip-load curves of the specimens a) SP-1A, SP-1B and SP-1C; b) SP-2A, SP-2B



a) *b)*

Fig.8: Slip-load curves of the specimens a) SP-3A and SP-3B; b)SP-4

6. CONCLUSIONS

A novel shear connection mechanism is proposed for use in demountable steel concrete composite beams utilizing hollow-core precast slab units. The structural behaviour of the proposed system was investigated by performing eight horizontal push out tests.

Push out specimen	Yielding force F_{EXP} [kN]	Maximum force F_u [kN]	Slip at max. force s_u [mm]	Yielding force F_{THEORY} [kN]	Ratio F_{EXP}/F_{THEORY}
SP-1A	220	320	23	230	0.95
SP-1B	250	380	30	230	1.08
SP-1C	250	360	20	230	1.08
SP-2A	130	260	19	150	0.86
SP-2B	130	250	30	150	0.86
SP-3A	170	300	19	186	0.91
SP-3B	170	340	35	186	0.91
SP-4	200	360	35	220	0.90

Table 2: Experimental results and yielding strength prediction

The deconstruction was implemented by disassembling one push out specimen and reassembling a new one using the undamaged structural components. The steel section and the precast concrete units were reused in a new test without affecting the structural behaviour. The following conclusions are drawn:

1. The push out tests showed that the proposed shear connection mechanism can provide a predictable force-slip behaviour, with strength and stiffness that can be adjusted based on the geometrical properties of the ‘yielding pocket’ (YP).
2. Compared to a conventional welded shear stud, the proposed shear connection mechanism can achieve higher strength, comparable initial stiffness, and much higher slip capacity, exceeding the requirement proposed by the Eurocode 4.
3. The slab units can be easily separated from the YP by removing a small amount of concrete, thus allowing for easy deconstruction and reuse of components.

7. REFERENCES

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