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Alternative Fastening Mechanism for Shear Connectors with Cold-Formed Steel Shapes Involved in Composite Sections

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Abstract. Over the past few decades, the use of steel-concrete composite sections has increased globally, in order to take advantage of compression strength in concrete and tensile strength in steel, ensuring its fastening through stress transfer elements denominated shear connectors. The main connection systems endorsed by the current design codes are used by applying welding as fastening mechanism to fix connectors. However, this thermal procedure produces concentration of residual stresses during cooling process, and risk of perforation in Cold-Formed Steel sections (CFS), affecting the behavior efficiency of the composite sections. In this research, self-drilling screws are proposed as an alternative mechanical system for connectors fastening. An experimental program was carried out to validate capacity and performance of the system, through Full-Scale Beam Tests. According to results, self-drilling screws are a viable alternative to be used as fastening mechanism in shear connectors for CFS and concrete composite sections. Composite system achieved to develop full capacity, even in inelastic range, without disconnection between materials. Self-drilling screws remained fixed on steel shapes without mechanical damage, allowing greater deformations, than structural service conditions.

Introduction

The basic principle of steel-concrete *composite sections* is to take advantage of their mechanical properties. In this way, steel sections can be loaded to high compression force, but efficiency is reduced in slender members due to their potential instability induced by lateral buckling, torsional buckling and/or local buckling, mainly in open sections [1]. Therefore, optimization of the composite section is based on the concrete slab to withstand compression stresses and the steel shape to withstand tensile stresses.

Assembly of composite sections implies attachment of stress transference elements between materials, called *shear connectors*. These components can control possible uplifts and differential displacements on the connection interface. Moreover, the strain state is also modified due to the inclusion of shear connectors, thus a two-materials system becomes a composite system.

Recently, within technologies with better structural efficiency, *Cold-Formed Steel (CFS)* sections have increased their structural applications in medium and small buildings [2], becoming a competitive alternative with respect to Hot-Rolled Steel (HRS) sections, which are heavier but commonly used in conventional infrastructure [3].

The main advantages of CFS are: versatility in the generation of different cross-sections, the possibility of using it in long spans, ease in industrial production, high strength-to-weight ratio, speed in packaging, transport and assembly [4]. Moreover, these sections are considered as an alternative for sustainability in construction [5][6][7].

Currently, design codes involve welding as a conventional methodology to fasten shear connectors [8][9][10][11][12][13][14][15]. This thermal process generates uncertainty in the structural behavior of the composite systems because it induces local residual stresses in steel sections and connectors, reducing both its mechanical capacity and efficiency. Moreover, in CFS, electrodes can perforate steel shape plates, due to high temperature and limited thickness of the steel section [16].

Therefore, knowing the disadvantages of welding, it is convenient to develop design methodologies, incorporating efficient alternative mechanisms for mechanical fastening of shear connectors [17].

In this research. self-drilling screws are validated as an alternative mechanical system to fix connectors. An experimental program was carried-out in order to quantify the failure capacity of system, involving Full-Scale Beam Tests. The advantages of the proposed system were confirmed according to the mechanical adhesion and structural behavior evidenced.

Background

Different alternative mechanical fastening systems in CFS sections have been studied, in order to ensure an adequate system connection, without depending on the welding process.

Hanaor [18], through experimental push-out test and full-scale beam test, evaluated bolts and nuts, and expansive bolts in hardened concrete, as shear connectors. Displacements and rotations were evidenced in the bolts due to adjustments and clearance of the bolt predrilled holes, inducing sliding between materials. Moreover, bolts presented ductile behavior, allowing to reach large deflections in the composite systems to be achieved.

Fontana & Bartschi [19], applied powder-actuated fastening systems to fix alternative shear connectors fabricated of CFS plates. Although the system was efficient, failure was given mainly by connector bearing, disassembling the composite systems.

Queiroz et al. [20], using bolted screws as transfer elements, evidenced local deformations in CFS sections, induced by stress concentration due to the limited thickness, reducing the capacity in the composite systems.

Lakkavalli & Liu [21] proposed to use self-drilling screws as shear connectors. The behavior of the composite systems was characterized by high inelastic deformations in screws and sliding of concrete on steel. These transfer elements presented limited capacity; thus, it was necessary to install many connectors, becoming a non-practical and expensive system.

All these types of shear connectors had an adequate connection and stress transfer between materials. In contrast, bolted joints have not been technically endorsed yet, due to the lack of standardization of the results.

Experimental Program

Bending tests on composite beams allow to characterize the global behavior of the fastening system during service conditions, acting as link between shear connectors and steel section. In this research, 4-points load experimental bending tests were carried out. Deformation states and final deflection system were evaluated, as well as maximum failure loads and failure modes. In Fig. 1 setup of experimental tests is presented. Configuration of specimens is defined in Table 1.

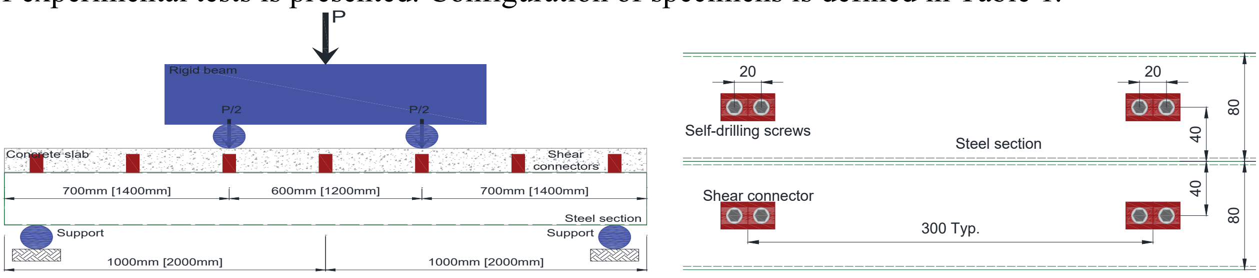


Figure 1. a) Four-points bending test setup. b). General arrangement of shear connectors. Top view. (Units: mm).

Table 1. Configuration of specimens in full-scale beam test.

	Concrete Slab		Steel Section			Shear Connectors	
No	Compressive Strength (f´c) (MPa)	Thick. (mm)	Yield Strength (fy) (MPa)	Thick. (mm)	Length (m)	Thick. (MPa)	Yield Strength (fy) (mm)
21-2	21.0	100	340	2.5	2.0	240	1.9
21-4	21.0	100	340	2.5	4.0	240	1.9
28-2	28.0	100	340	2.5	2.0	240	1.9
28-4	28.0	100	340	2.5	4.0	240	1.9

Results and Discussion

The fastening capacity was preliminary tested by Screw Shear Test, achieving to identify the failure loads and failure modes on the individual system. Results are presented in Fig. 2. The ultimate nominal limit states are also included as horizontal lines.

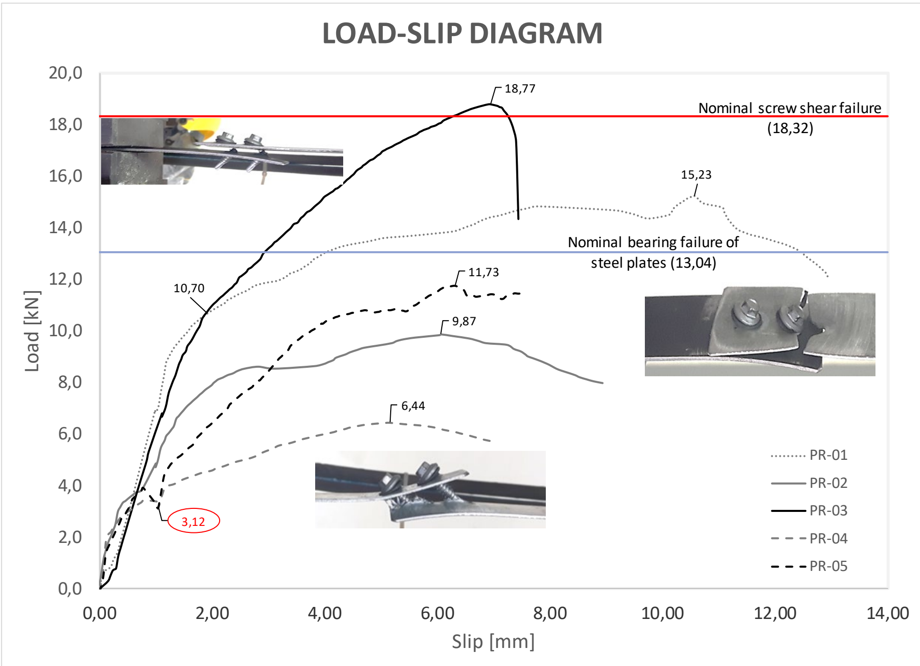
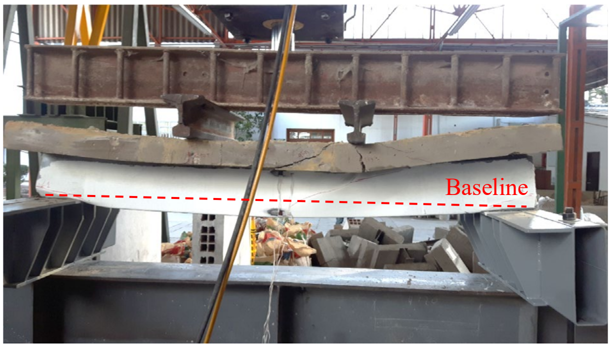


Figure 2. Load-slip curves for experimental screw shear test.

An analytical study was made, which allowed predicting the nominal failure loads under bending loads. According to AISC-10 [8] and Eurocode 4 [14] recommendations, this type of non-compact steel shapes should be analyzed under elastic methods, due to the susceptibility to local buckling in steel plates. This condition avoids developing the plastic capacity on the entire steel section before the failure of the composite system. Fig. 5 shows the nominal loads, applying *Strain Compatibility Method (SCM)*, by transforming concrete cross section into an equivalent steel section.

Although steel plastic capacity cannot be developed, Fig. 5 also includes plastic analysis applying *Plastic Stress Distribution Method (PSDM)*, in order to know a possible range of workloads before failure. Full composite action was considered in both analyzes.

The typical final condition of specimens after the experimental test is shown in Fig. 3.



a). b).

Figure 3. Final condition of specimens in full-scale beam test. a). 4m-long beams. b). 2m-long beams.

Deflections are compared with baseline, showing large displacements and exceeding widely elastic behavior of the systems (more than 1.7 times for 4m-long beams and more than 2.5 times for 2m-long beams).

The 2m-long beams showed elastic and maximum deflections around 30% and 50% respectively, with respect to 4m-long beams, due to the direct relationship existing with the length of elements.

Test instrumentation allowed to record vertical and longitudinal displacements. Then, deflection curves are presented in Fig. 4. Beams length were normalized. The figure includes displacements at midspan and thirds in length. In addition, baselines of the service limit state were included, in order to compare the final condition of specimens. It is evident that the composite sections behavior remains in the elastic range under service conditions, regardless of compressive strength of concrete, which becomes representative in later states (Figures 4 and 5).

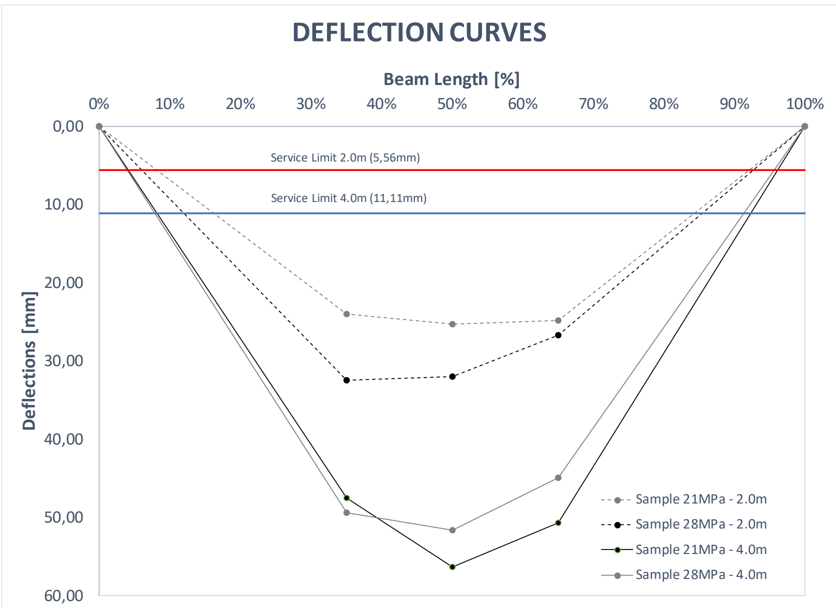


Figure 4. Deflection curves for experimental full-scale beam test.

Based on the curves behavior, maximum states of the system deformation exceed about 5 times the limits for service condition.

Fig. 5 shows Load-Deflection curves in 2m-long beams and 4m-long beams. Nominal elastic and plastic limits are included as expected range of structural behavior, as well as service limits.

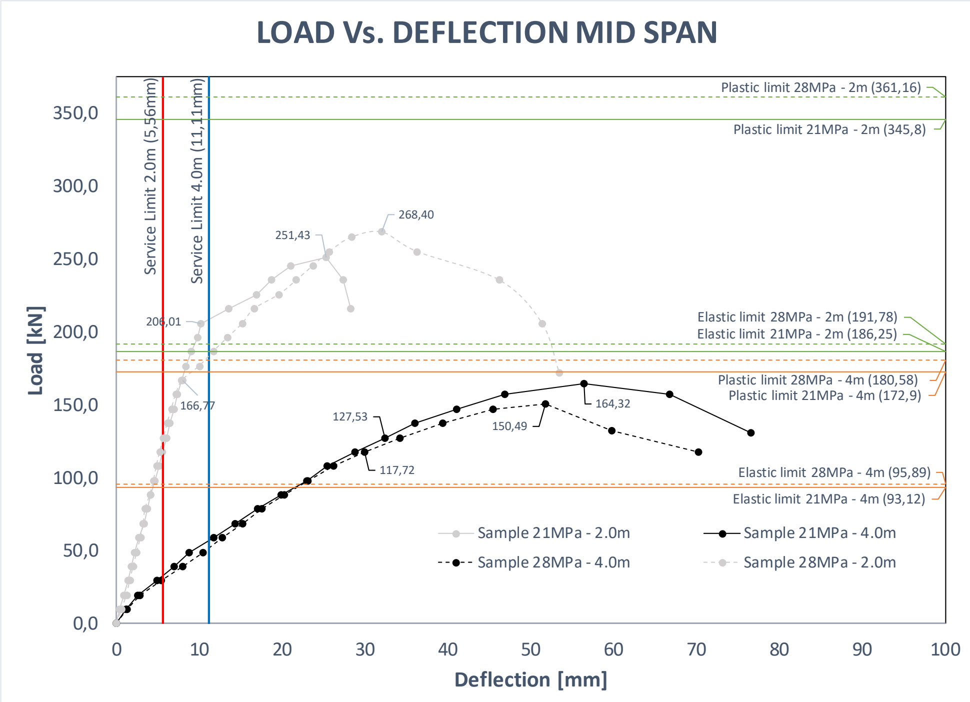


Figure 5. Load-Deflection curves for experimental full-scale beam test.

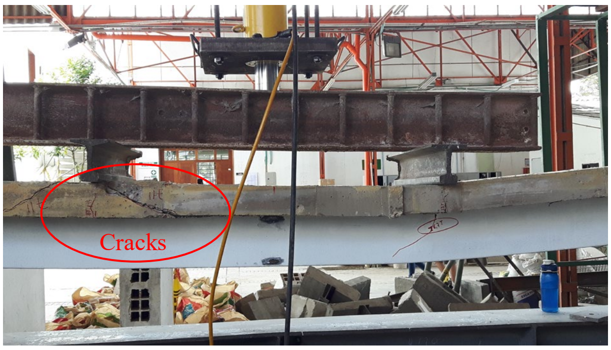
On the one hand, 4m-long beams showed a behavior close to the nominal plastic load capacity of the composite section, 95% in 21MPa concrete and 83% in 28MPa concrete. In addition, elastic loads exceeded the nominal limits 1.37 times and 1.22 times in 21MPa and 28MPa, respectively.

Deflections at maximum load evidenced 1.09 times greater in 21MPa concrete.

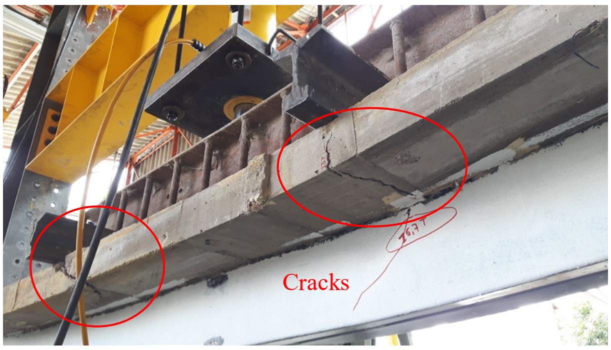
On the other hand, the 2m-long beams maximum loads are in an intermediate state between plastic and elastic nominal conditions. In this way, these loads reached around 70% of nominal plastic load. Elastic loads are around ±10% close to predicted nominal values. Maximum deflection was presented in 28MPa concrete, being 1.26 greater with respect to 21MPa concrete.

Differences in elastic deflections were around 3mm between the same length specimens.

Once elastic behavior is exceeded, cracking and fracture are induced in slab concrete, mainly at the load application site, as shown in Fig. 6.



a).



b).

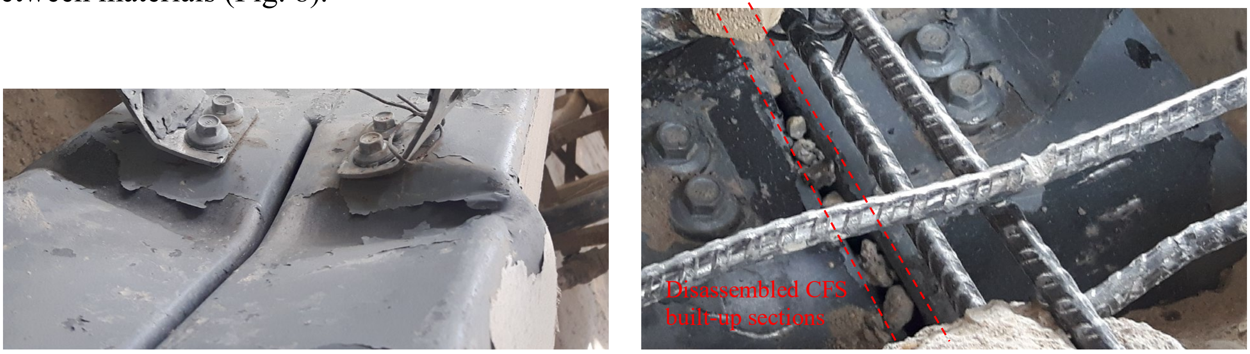
Figure 6. Concrete slab fracture in full-scale beam test. a). General view. b). Detailed view.

Similarly, in the steel section, local buckling is generated due to an increase in the load. Displacements of the steel plates outside the load plane are produced, as shown in Fig. 7, and asymmetry in the final condition of deflections (Fig. 4).

a). b).

Figure 7. Local buckling in steel shape in full-scale beam test. a). General view. b). Lateral plate detailing.

Once the experimental tests were completed, the concrete slab was removed, in order to know the final state of the shear connectors fastening system after working as elements of stress transferring between materials (Fig. 8).



a). b).

Figure 8. Final state of self-drilling screws fastening system. a). Local buckling on CFS shapes. b). Separation in closed built-up section.

According to Fig. 8, self-drilling screw system kept integrity by itself. Shear connectors remained attached to the CFS shape, with no evidence of local affectation by tearing in perforations, nor by shearing in screws. System deformation was governed mainly by local buckling in steel section and, to a lesser extent, cracking in slab concrete. Thus, CFS becomes the restrictive element in the capacity of composite systems.

Likewise, intermittently welded CFS built-up section was disassembled, due to high displacements.

Based on the results evidenced in this study, it can be concluded that the self-drilling screws fastening mechanism of shear connectors achieves a stable join. It is capable to develop a high capacity of stress transfer in the interface between materials, allowing large deflections in the composite section, without local affectation or detachment of the system.

Conclusions

In this research, self-drilling screws were characterized as an alternative fastening mechanism. Its mechanical capacity during the transfer of stresses into composite systems was validated through experimental tests, becoming an alternative welding replacement, mainly in CFS shapes.

The mechanism allowed composite sections to develop an inelastic capacity before presenting local affectations caused by local buckling in CFS sections, without becoming the weakest element of the system. In addition, recorded deflections exceeded the service limits widely without evidence of screws detachment, showing high ductility.

The ultimate capacities in full-scale beam test were within the nominal range (elastic-plastic), approaching the plastic behavior in 85% and 70% in 4m-long beams and 2m-long beams respectively, which allows to establish analytical capacity predictions in both cases, which exceeded elastic capacity as suggested in design codes.

According to the experimental results of screw shear tests, plates with more than 2mm thickness presented failure mechanism caused by shear screws, while with lower thickness, they failed due to bearing plates or tension on net section in plate in the thinnest plate but showed greater ductility.

CFS samples are particularly susceptible to be affected in their mechanical properties during experimental tests, due to the limited thickness. Therefore, procedures must be highly controlled in order to avoid alterations in data record.

The self-drilling system has a better structural performance as fastening mechanism, due to its high mechanical strength, and ease to be implemented in construction.

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