PROPOSAL OF A THREE-DIMENSIONAL SEMI-RIGID COMPOSITE JOINT: TEST AND FINITE ELEMENT MODELS.

Beatriz Gil*, Rufino Goñi* and Eduarbo Bayo*

* Department of Structural Analysis and Design
University of Navarra, 31080 Pamplona (Navarra), Spain
e-mails: bgilr@unav.es ; rgonil@unav.es ; ebayo@unav.es

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***Abstract**. In sway structures the stability has to be assured within the two main axes of the frames. By means of semi-rigid joints, the lateral stability of the structure may rely on the stiffness and ductility of the joints, thus avoiding bracing systems. This paper proposes new designs that include beams attached in a semi-rigid manner to both, the major and minor axes of the column. This new three-dimensional design for semi-rigid composite joints has been tested and the results are presented in this paper. The experimental program consists in two 3D semi-rigid composite joints under non-proportional loads and one façade joint. These tests provide information as to whether the joints satisfy the requirements of the EC3 in terms of ductility or not. Also the interactions in the proposed joint caused by loads in both directions are studied.*

1 INTRODUCTION AND OBJETIVES

Semi-rigid composite joints not only have the advantage of optimizing the use of the material, but also of providing lateral stiffness for sway frames. By means of semi-rigid joints, the lateral stability of the structure may rely on the stiffness and ductility of the joints, thus avoiding bracing systems. The stability of the structure has to be assured within the two main axes of the frames. The proposed design includes beams which are attached in a semi-rigid manner to both, the major and minor axes of the column. The design of the major axis connection is made with a bolted flush end plate and the central rebars of the slab passing through the column flanges, while that of the minor axis is built by means of an additional plate welded to the column flanges, instead of attaching it to the column web.

The behavior of semi-rigid 2D composite joints has been widely investigated and tested. However, the behavior and interaction in the 3D joints has been studied barely (Green et al. [1], Dabaon et al [2]). The Eurocodes (EC3 [3] and EC4 [4]) provide general rules for the design of joints but do not consider cases such as 3D joints and/or joints attached to the minor axis.

This paper presents the results of an experimental program consisting in one 3D semi-rigid composite internal joint under proportional loads, a similar one subjected to non-proportional loads and one façade joint. These tests provide information as to whether the joints satisfy the requirements of the EC3 and EC4 in terms of ductility and resistance. Also the interactions in the proposed joint caused by loads in both directions are studied. Simultaneously, finite element modeling with the same characteristics as the specimens is carried out and calibrated against the experimental results. This model will be used to develop a parametric study and obtain analytical methods for the design of this joint typology.

2 PROTOTYPES DESCRIPTION AND EXPERIMENTAL RESULTS

A design of three-dimensional semi-rigid composite joint, that is, a column with composite beams attached to both the strong and the weak axis, is proposed and tested. This design is based on those previously proposed by Gil and Bayo [5], [6] for 2D composite joints, and by Cabrero and Bayo [7], [8] for 3D steel only joints.

The experimental program consists on one test of a three-dimensional internal semi-rigid composite joint subjected to proportional loads (test E01), a second one consisting on a three-dimensional composite joint subjected to non-proportional loads (test E02), and a third one consisting on one three-dimensional composite joint with one beam on the major axis and two beams in the minor axis (test E03), that is, a joint on a external façade. In all of them, the design of the major axis connection is made with a bolted flush end plate and the central rebars of the slab passing through the column flanges [5], while that of the minor axis is built by means of additional plates welded to the column flanges, instead of attaching it to the column web [1, 7].

This design has been chosen instead of attaching the beam to the column web due to several advantages such as:

- The additional plates placed in the tension and compression area of the column flanges add stiffness and strength to the web, especially when it is subjected to non proportional loads.
- The joint is simpler to build than the same joint attached to the web.
- The joint becomes more resistant and ductile, avoiding possible instability of the column web.
- The gap between both plates attached to the minor axis the facilities the placing and tighting of the bolts.

The choice of geometry and materials has been made in accordance with Eurocode 2 [9], Eurocode 3 [3] and Eurocode 4 [4]. The sections, bolts, etc. of the three specimens are shown in the next table:

Table 1: Configuration of specimens

Test	Column	Slab	Axis	Viga	End Plate	Bolts	Rebars	L 1	L 2
E01	HEB 180	10 cm H30	Major	IPE 270	10 mm	T 16 (10.9)	6Ø16	1,2 m	1,2 m
			Minor	IPE 180	10 mm	T 12(10.9)	9 Ø12	1,2 m	1,2 m
E02	HEB 180	10 cm H30	Major	IPE 240	10 mm	T16 (10.9)	6Ø16	1,0 m	1,2 m
			Minor	IPE 200	10 mm	T 12(10.9)	9 Ø12	1,0 m	1,0 m
E03	HEB 180	10 cm H30	Major	IPE 240	10 mm	T16 (10.9)	6Ø16	1,0 m	1,2 m
			Minor	IPE 200	10 mm	T 12(10.9)	5 Ø12	1,0 m	1,0 m

3.1 TEST E01

The test configuration and loading pattern for the first specimen are shown in Figure 1. The specimen is placed face down and the load is applied to the top of the column. The end of each beam is supported on a load cell that measures the corresponding reaction in that support. Since the length of the beams in every axis is the same, the specimen is symmetric and the applied loads are proportional.

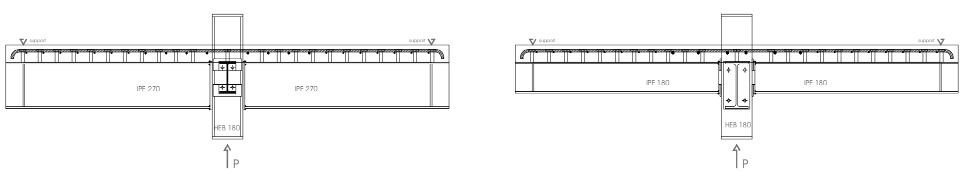

Figure 1: Tests configuration (E01)

Regarding the instrumentation, the load is introduced in the top of the column by means of two hydraulic jacks that feature 400 kN each. The reactions in the beams are measured with load cells with a limit of 200 kN. Two inclinometers are placed in the weak axis beams, close to the column; the third is placed in one of the strong axis beam and the fourth in the column web. A displacement transducer is used to measure the deflection at the bottom of the column and finally, strain gages are placed in the relevant components of the joint (plates, flanges, webs and rebars) in order to obtain qualitative information on the sequence of the yielding process. The load is applied in two stages. In the first one, the column is loaded progressively up to 200 kN and then is completely unloaded. In the second stage, the specimen is loaded progressively until failure.

Results: the tested joint shows a nonlinear behavior at early loading stages, as shown in the column load- deflection curve of Figure 2. This is due to the small tensile strength of the concrete whose cracks spread and grow with increased loading. The total load applied in the column is greater than 500 kN and the column deflection reaches almost 60 mm.

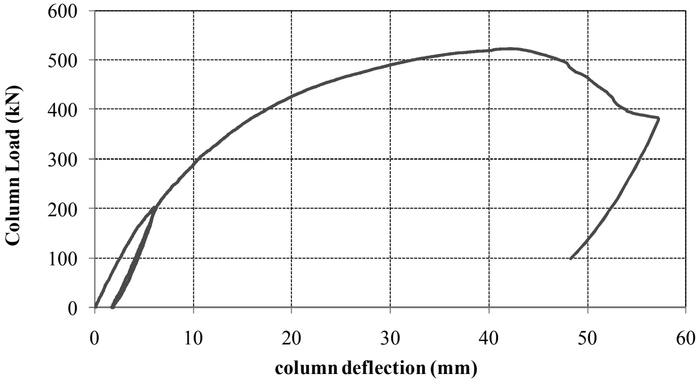

Figure 2: Applied load at the column vs deflection

Figure 3 shows the moment-rotation curve for a major axis joint and the minor axis one. It may be seen that the maximum moment in the major axis joint is around 150 kNm and the maximum rotation reached is 30 mrad. There are several steps at the end of the curve, due to the yielding of the components. The complete collapse of the joint is produced when suddenly a shear stud is broken due to the longitudinal shear. This shear is high due to the interaction of the loads in both directions. Prior to the stud failure, the additional plate in compression, the column web in compression and the rebars of the strong and weak axis had yielded. The minor axis joints reach a moment of around 40 kNm and a rotation capacity of 50 mrad, thus showing a quite ductile behavior.

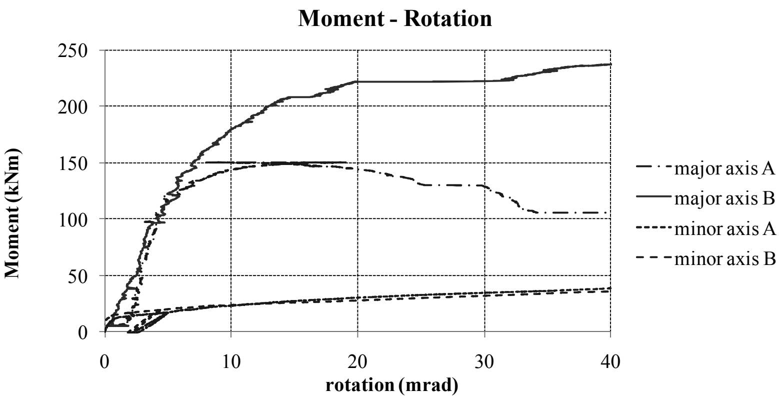

Figure 3: Moment-Rotation curves

When the specimen fails, there are two components in the minor axis that have yielded: the additional plate in compression and the reinforcement. The rest of the components in this axis remain in the elastic range. Regarding the response of the joint, it may be observed that the major axis joint shows almost the same initial stiffness in both sides, which is logical due to the symmetry of geometry and loads. The strength was also supposed to be same in both sides but this does not happen because of possible imperfections and asymmetries in the joint and/or the concrete slab. The difference between the moments in both sides is absorbed by torsion in the minor axis beams.

3.1 TEST E02

The test configuration and the loading pattern for the second specimen are shown in Figure 4. The column has pinned ends, and the joint is firmly attached to the floor and the ceiling, which absorb the vertical and horizontal reactions. A constant load of 20 kN is applied in both edges of the minor axis, and kept constant during the whole test. In the edges of the major axis, the load is applied by controlling the displacements. The displacement in one side is triple than the displacement on the other side in order to get different moments on both sides of the column. The purpose is to reproduce the case of frames subjected to lateral wind loads and to check the reliability of the joint.

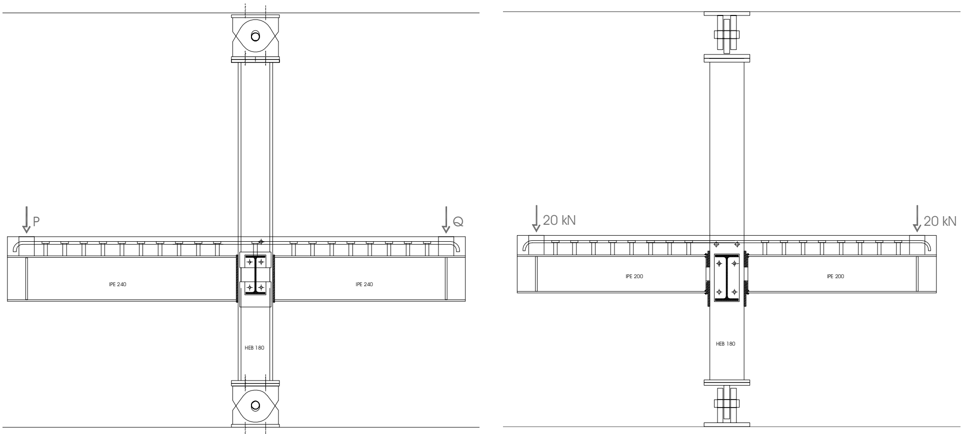

Figure 4: Test Configuration (E02)

The aim of this load pattern is to study the interaction of the web panel in shear with the rest of the components of the joint. Another aim is to analyze the benefits or drawbacks derived from the fact that the joint is loaded in both axes and, in the same way, the benefits or drawbacks derived from the additional plates in the minor axis of the proposed joint.

Results: the moment rotation curves for the major axis of the second tested joint (E02) are shown in Figure 5.

We distinguish the side with a larger moment (side A) than that with a lower moment (side B). Several facts resulting from the test are worth mentioning:

a) The sections at each connection do not remain plane after deformations. Thus, the connection rotation at the external plate level is different from that at the slab on the same vertical.
b) The stiffness of the connection is such that the side with the lower moment has a larger stiffness.
c) The converse is true for the resistance, that is, the more loaded connection has more resistance.

It may be seen how the major axis rotation in the more loaded side (A) reaches 80 mrad which satisfies the requirements of the Eurocode by a large margin. The major axis joint in the opposite side (B) reaches 30 mrad at the time of failure. This rotation is lower because, when the side A fails, the reinforcement, which is part of both joints, has already yielded (that is also the reason why the strength is lower). In any case it also satisfies the EC3 rotation requirements.

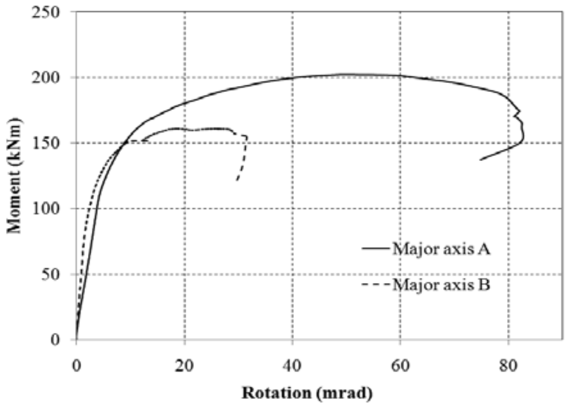

Figure 5: Moment-Rotation curve for the major axis joints (test E02)

The component yielding sequence is obtained by means of the strain gages placed on them and it is the following:

- The first component that yields is the reinforcement in both mayor and minor axis. Despite of the fact that the minor axis is not loaded until failure, the minor axis reinforcement yields because the mayor axis reinforcement pulls the minor axis one. This also induces an additional shear in perpendicular direction to the minor axis beam, at the interface between the steel beam and the concrete slab, so the shear studs bears more shear than if the structure were loaded in only one axis.
- The additional plates in the minor axis yield after the reinforcement, followed by the beam flange in compression.
- Finally, the flush end plate of the mayor axis joint yields.

The moment rotation curves for the minor axis are shown in the Figure 6. As the minor axis is only loaded up to 20 kN, the curve shows a linear behaviour and only the stiffness can be obtained.

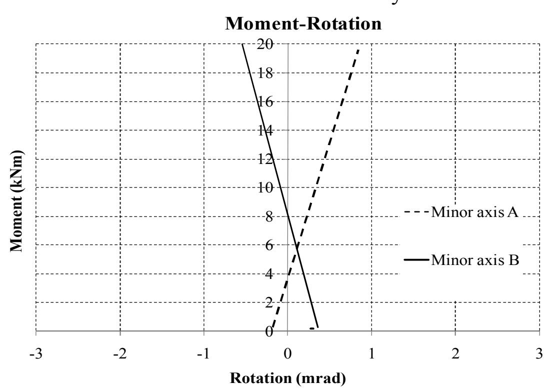

Figure 6: Moment-Rotation Curve for the minor axis joints (E02)

3.1 TEST E03

The third test has the same configuration and sections as in the previous one, except that this one lacks one of the major axis beams (Figure 7). The aim is to reproduce the case of joints attached to columns placed in the perimeter of the building (façade columns). The reinforcement is bent as shown in Figure 7, in order to guarantee the required anchorage length.

The edges of the minor axis are loaded up to 50 kN and this load is kept during the whole test, meanwhile the major axis joint is loaded and unloaded in a first stage to get the initial stiffness, and then it is loaded until failure in the second stage.

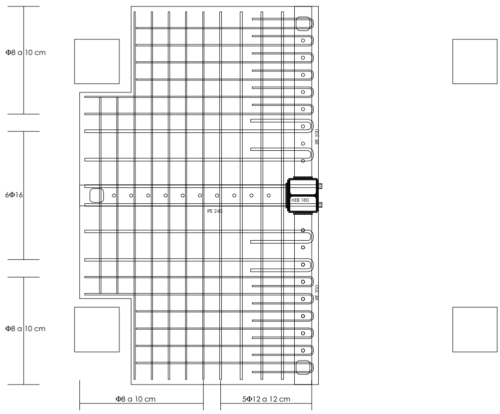

Figure 7. Test E03 configuration

4 FINITE ELEMENT MODEL

4.1 Geometry and Definition of the elements

A finite element model is developed by means of the ABAQUS program. The three-dimensional FE model (Figure 8) has the configuration and dimensions of the tested specimens.

The concrete slab, the slab reinforcement, the steel beams and column, the bolts and even the shear studs are modeled with 8-node solid elements with reduced integration (C3D8R). The reduced integration element has been chosen instead of incompatible modes (C3D8I) to avoid the shear locking that it is produced with the C3D8I element.

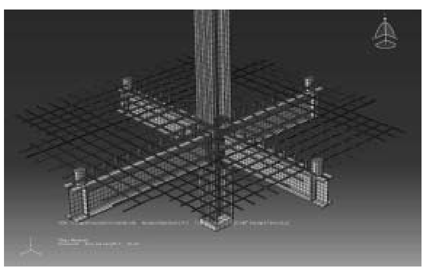

Figure 8. Finite element model.

4.2 Interactions, Boundary conditions, materials and analysis

The interactions between the different materials are modeled in the following way:

The reinforcement and the shear studs are embedded in the slab. This technique eliminates the translational degrees of freedom of the embedded nodes and makes them correspond with those of the host element. Solid elements have been chosen to capture the deformation of the connectors properly, and avoid the use of springs use (Queiroz et al. [10] and Dabaon et al. [2]). Surface to surface contact interactions are defined between the end plate and the column flange. The bolt head and the nut are tied to the plates to simplify their interaction.

The materials chosen for the finite element model are the same as those in the specimen: S275 for structural sections and plates, B500SD for reinforcement, C30 for the concrete, and the shear studs with strength of 450 N/mm2. The real stress-strain curves are introduced.

A second order inelastic analysis is carried out using displacement control, which allows us to monitor possible drops in the load displacement and stress-strain curves. This method also allows us to reproduce the real conditions of the load pattern carried out in the tests.

4.3 Comparison with experimental results and model validation

Figures 10 and 11 show the load-deflection and moment rotation curves for the validation of the numerical model with the experimental results of the E01 and E02, respectively.

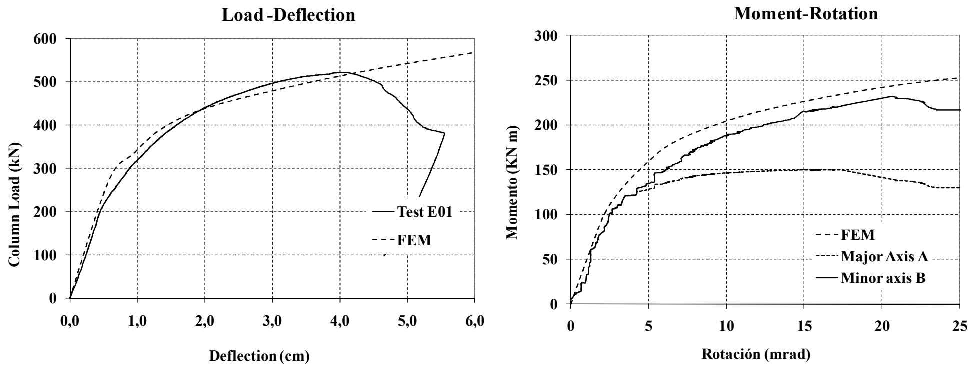

Figure 10: Validation of the FE model with the experimental results for E01

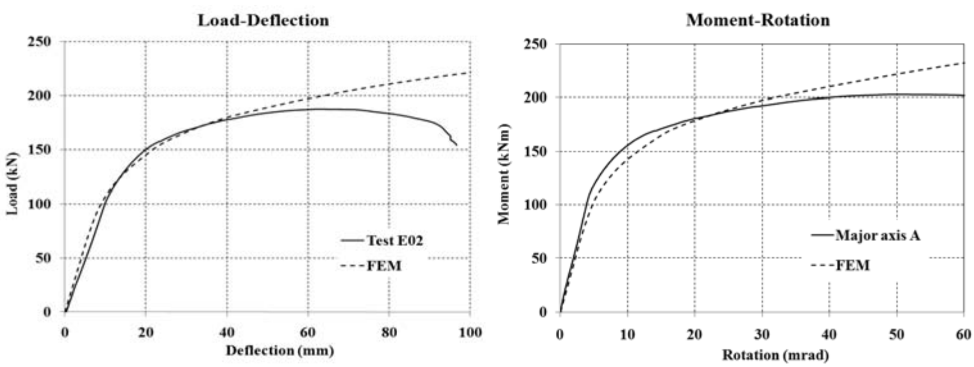

Figure 11: Validation of the FE model with the experimental results for E02

It may be seen how the stiffness and the strength in all the curves are captured accurately. However, the finite element model does not represent the rotation capacity due to the impossibility of the concrete model of the Abaqus program of capturing the concrete failure.

5 CONCLUSSIONS

A design for three-dimensional semi-rigid composite joints is proposed and tested. The purpose of this design is to give lateral stability in sway frames, that is, to bear not only vertical but also lateral wind loads. The strong axis connection of the proposed joint is carried out by means of a bolted flush end plate with the central rebars of the slab passing through the column flange. The weak axis connection is materialized by means of an additional plate welded to the column flanges, rather than attaching the beam to the column web. This design is tested under proportional and non-proportional loads.

The 3D joint shows a good behaviour in both axes. The additional plates of the minor axis affect the behavior of the whole joint, which is quite sensitive to their dimensions. It is recommended to enlarge the lower plate up to the lower major axis beam to add stiffness to the column web panel in shear and compression. The tested joints are quite ductile (over 30 mrad). However, when non proportional loads are applied, the side that bears the lowest load shows higher stiffness but lower strength due to the yielding of common components for both sides, such as the rebars.

Further work is need to assess the interaction between minor and major axis with non proportional loads. A parametric study is being carried with this aim, by means of finite element models calibrated with the experimental results.

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