Experimental and numerical study of an original demountable composite concrete steel beam made of concrete blocks

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RESUME This article aims to study the flexural behavior of demountable composite beams made of concrete panel blocks bolted together with steel HEA 160 beam sections as part of the Colabor project led by MECD. Such interesting technological solution emerged as an attempt to develop more sustainable constructions and to reduce the environmental footprint of existing constructions by promoting their reuse. An experimental campaign was conducted in parallel to the development of a numerical model on Abaqus to show the efficiency of the proposed solution and to study the impact of different concrete panels and bolt configurations (number and dimensions of panels, types of bolts, *etc.*) on the overall behavior of the composite structure. Since such bending behavior depends on the shear connectors used between concrete and steel, push-out tests were performed on bolts (shear connectors) connecting concrete panels and steel profiles to determine their constitutive law.

Mots-clefs Composite, concrete/steel, demountable beams, reuse, bolted connections.

I. INTRODUCTION

Composite structures made of different materials were developed in order to take advantage of the interesting properties of the individual materials in a way to build an assembly that has better mechanical and/or thermal properties than the ones of the individual materials. Reinforced concrete is a good example of composite materials where steel is combined with concrete in a way to have a less expensive structure where the weakness of concrete in tension is overcome by steel.

In Civil Engineering, when building mixed structures, non-demountable solutions are often used. Indeed, in the case of a concrete slab combined with a steel profile, concrete is usually poured on top of the steel profile to form a composite structure using studs. Recently, numerous research studies were conducted to analyze the behavior of shear connections using welded or bolted connectors in order to compare the behavior of various demountable connectors with the well-known welded connectors [1][2][3]

This research project aims to study both experimentally and numerically an original demountable solution where concrete panel blocks are bolted together with steel HEA beam sections to form an assembly where the two materials are capable of working together. The advantage of such solution is that it is more sustainable since it can be reused (the different concrete panels as well as the steel beam section can be demounted and reused in other projects).

Connections used in such solution have an important role on the overall behavior of the assembly [4] [5]. In fact, they are the elements that transfer the loads between the different parts in a way to ensure a composite behavior (similar deformations in both materials). To characterize the behavior of such connections, pushout tests were experimentally performed considering different concrete block thicknesses (6 cm or 10 cm) and different bolt configurations (M12, M16, *etc*.). Then, 3-points bending tests were performed on beams made of concrete panels bolted with HEA 160 steel beams. Again, the experimental campaign aims to characterize the behavior of such beams considering different scenarios (number of blocks, dimensions of bolts, *etc.*).

In this article we will present analytical, experimental, and numerical results obtained on one connection configuration (M16 bolts and concrete blocks having a thickness of 6 cm and a length of 100 cm) since for the other configurations, experiments are still ongoing.

In a first section, we will present the experimental and numerical results obtained when performing pushout tests with the connection configuration considered.

In a second section, we will present the experimental results obtained when performing a 3 points bending test on the composite beam under study (having the same connection configuration considered in the pushout test). Results obtained experimentally will be compared with analytical ones (assuming a perfect composite section behavior).

II. Numerical and experimental results of the pushout tests

A. Material properties

Concrete panels considered in this study have the mechanical properties that are given in Table 1. Concrete mechanical properties were identified experimentally by testing concrete cylindrical specimens made of the same concrete mix that was used to build the concrete blocks. The mechanical properties of the HEA 160 steel beam were determined by cutting small specimens from the web and the flange of the HEA 160 steel profile and then testing them (HEA 160 steel properties are given in Table 2). The M16 bolts where also tested to determine their yield stress and ultimate strength (characteristics given in Table 3).

TABLE 1. Concrete material properties

Compressive Strength (MPa)	Young Modulus (GPa)	Tensile Strength (MPa)
35	32.8	3.5

TABLE 2. HEA 160 material properties

Young Modulus (GPa)	Yield Stress (MPa)
210	358

TABLE 3. M16 bolts material properties

Young Modulus (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)
205.9	922.6	982.4

B. Experimental test set-up and results

The set-up that was used to perform the pushout test is given in Figure 1. The geometry of the concrete blocks (50 cm by 50 cm with a thickness of 6 cm) and of the HEA 160 are specified (50 cm long) as well as the position of the LVDT sensors (4 in total) that were used to measure the relative displacement between the steel HEA 160 profile and the concrete blocks, during the pushout test. In total, 8 M16 bolts were used. The vertical cyclic loading imposed on the HEA 160 profile using a vertical jack was measured using a load sensor as shown in Figure 2.

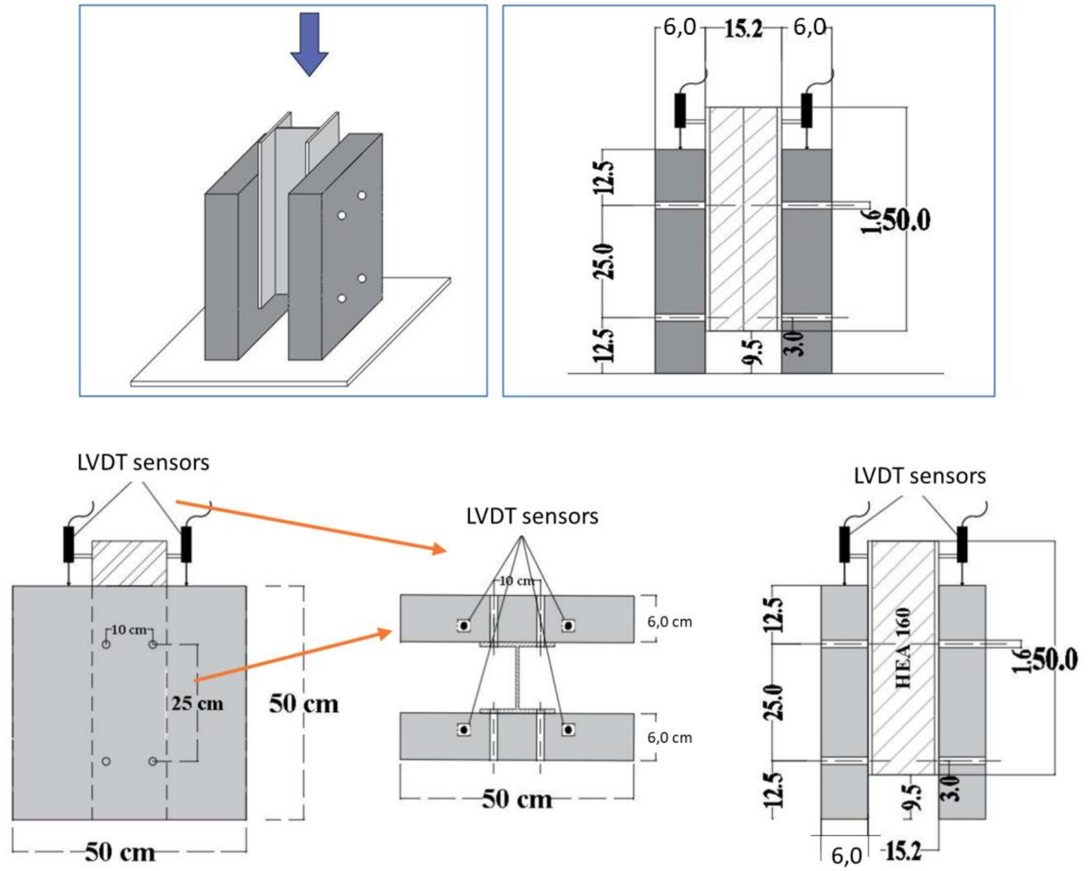

FIGURE 1. Experimental pushout-test set-up (positions of displacement sensors (LVDT) are indicated)

The experimental average curve obtained during the pushout static cyclic test performed is given in Figure 3 (average displacements measured by the four LVDT sensors were considered). The maximum force sustained during this pushout test was equal to 652 KN.

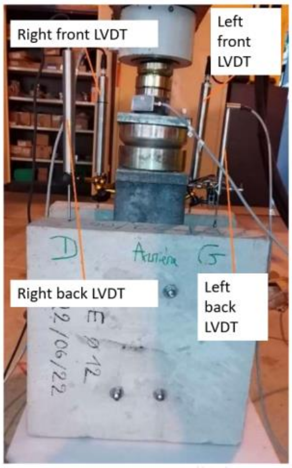

FIGURE 2. Experimental set-up of the pushout test performed to characterize connection behavior (the positions of the four LVDT sensors used as well as the vertical jack and the pancake load sensor used are shown)

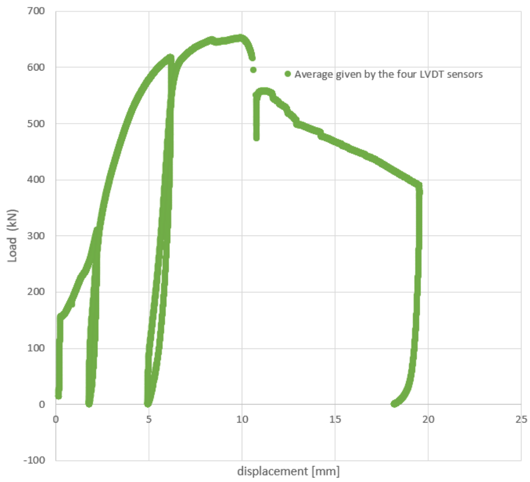

FIGURE 3. Experimental pushout test results (adopted configuration: M16 bolts and concrete blocks having a 6 cm thickness)

The observed failure mode corresponds to a shear failure of the bolts with the crushing of the concrete blocks.

C. Numerical model and results

The pushout test with the considered configuration (M16 bolts and concrete blocks having a thickness of 6 cm) was modeled on the Abaqus finite element software. Concrete panels, steel HEA profile as well as steel bolts were modeled using C3D8R finite elements (meshing used in the model is shown in Figure 4). Displacements were fixed at the bottom of the concrete blocks. A hard contact normal interaction was considered between elements as well as a tangential contact with a coefficient of friction equal to 0.35.

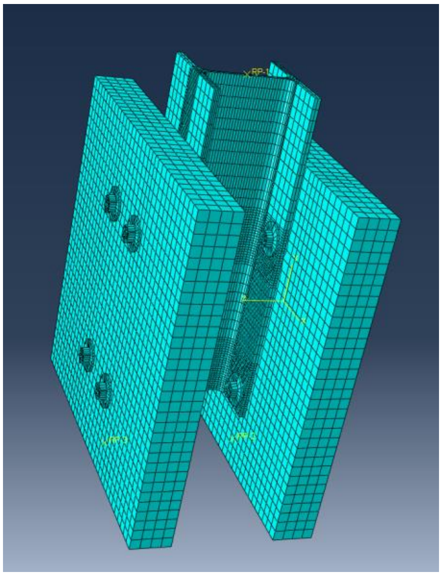

FIGURE 4. Meshing used to model the pushout test on Abaqus

Concrete behavior was modeled using the damage plasticity model on Abaqus. Concrete, stress versus strain and damage evolutions were calculated on MATLAB using the Model Code model [6] and implemented on Abaqus. Traction and compression damage evolutions as well as stress versus strain evolution used as inputs of the concrete damage plasticity model of Abaqus are given in Figure 5. Bolts and HEA 160 profile were modeled using a linear perfectly plastic model.

2 push out models were considered: a first model with no pretention on the bolts and a second model with a 55 kN pretention on each bolt (which corresponds to the pretention that was experimentally imposed). Figure 6 presents the comparison of numerical results with experimental ones. As shown in Figure 7, concrete cracks were observed experimentally during the pushout test. Similarly, at the same location, an important traction damage was observed numerically suggesting the formation of cracks.

The numerical model accounting for pretention allowed obtaining a maximum load of 650 kN versus 652 kN obtained experimentally). However the numerical model is globally stiffer than the experiment. It is due to the fact that, experimentally, holes were taken wider than the bolts which allowed a certain amount of play in the holes. In addition, not all bolts were centered in the holes, some were already in contact with concrete at the beginning of the test which increased displacements measured experimentally in comparison to what was obtained numerically. Furthermore, bolts were modeled as having a linear perfectly plastic behavior. In the reality, they have a more ductile behavior with strain hardening that should be accounted for in the numerical model developed.

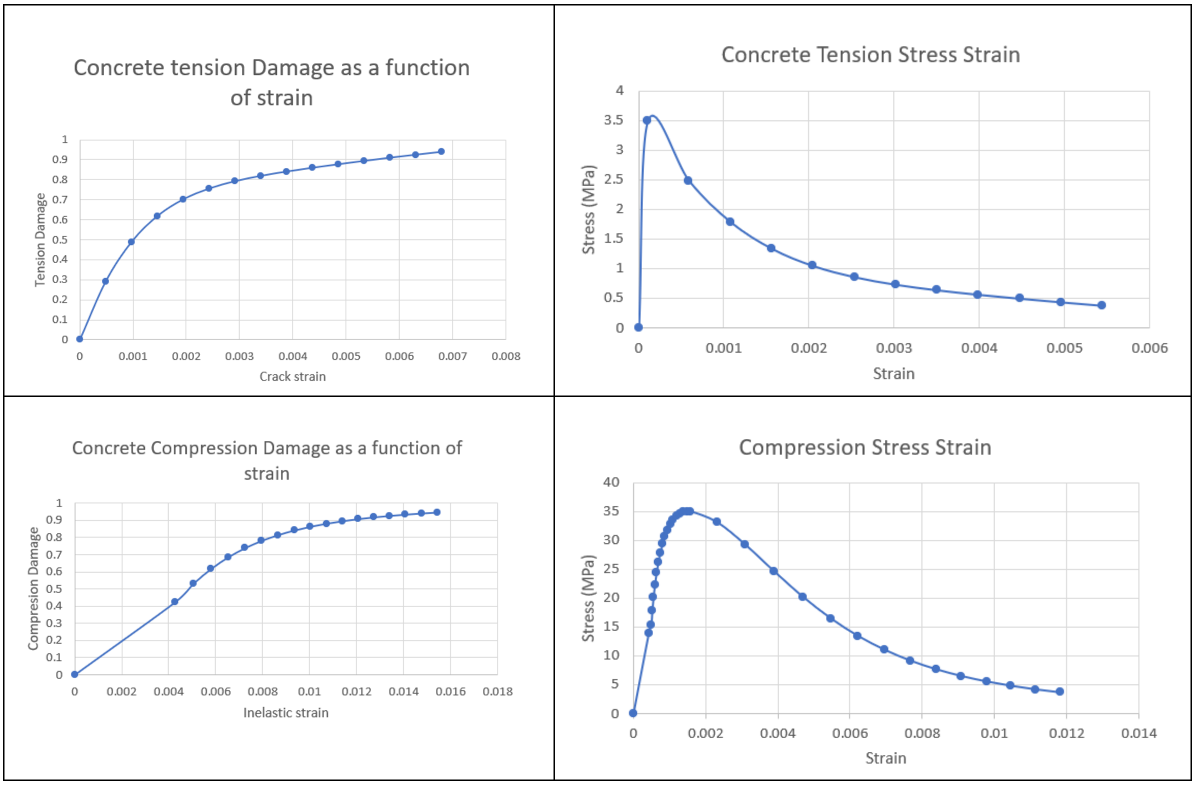

FIGURE 5. **Concrete constitutive law in compression and traction**

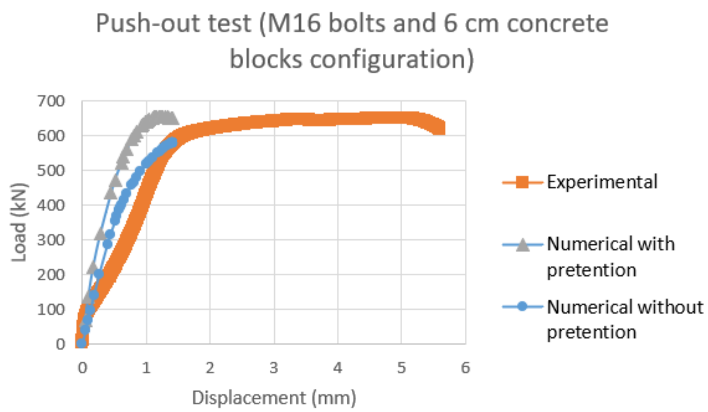

FIGURE 6. **Comparison of numerical and experimental push out test results**

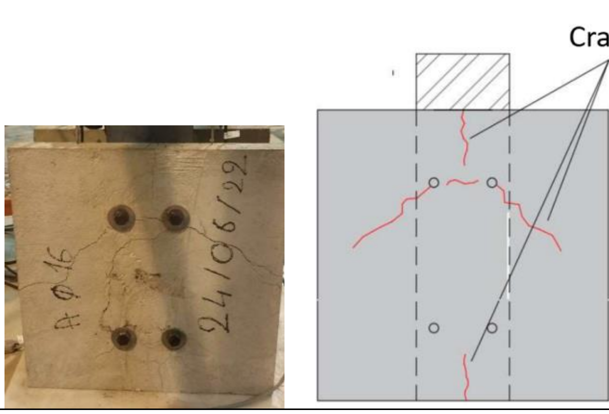	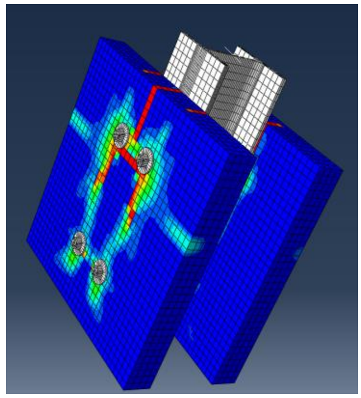
Concrete cracks during the pushout test	Concrete damage (observed numerically) Red color corresponds to a damage value of around 1

FIGURE 7. Observation of concrete cracks during the pushout test (both experimentally and numerically)

II. Experimental and analytical results on a 3 points flexural test

A. Experimental set-up and results

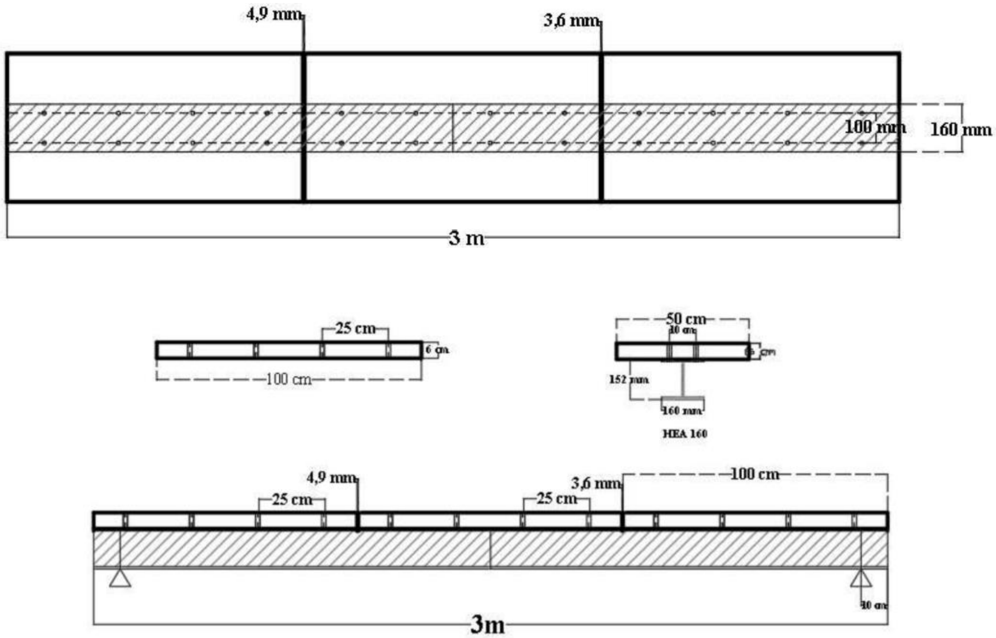

FIGURE 8. Demountable composite beam geometry

A beam made of three concrete blocks of dimensions 50 cm by 100 cm having a thickness of 6 cm and bolted to an HEA 160 steel beam having a length of 3 m, with M16 bolts was constructed. The dimensions of the concrete blocks, the steel beam and the spacing of the bolts are shown in Figure 8. This demountable beam was subjected to a 3-point flexural beam test to characterize its behavior. Concrete blocks, steel HEA 160 beam and steel M16 bolts are considered to have the mechanical properties notified respectively in Tables 1, 2 and 3. The test set up is shown in Figures 8 and 9 where the positions of LDVT and load sensors as well as the loading jack used are specified. Experimental results are shown in Figure 10. It can be seen that the maximum load sustained by the demountable beam is equal to 177 kN.

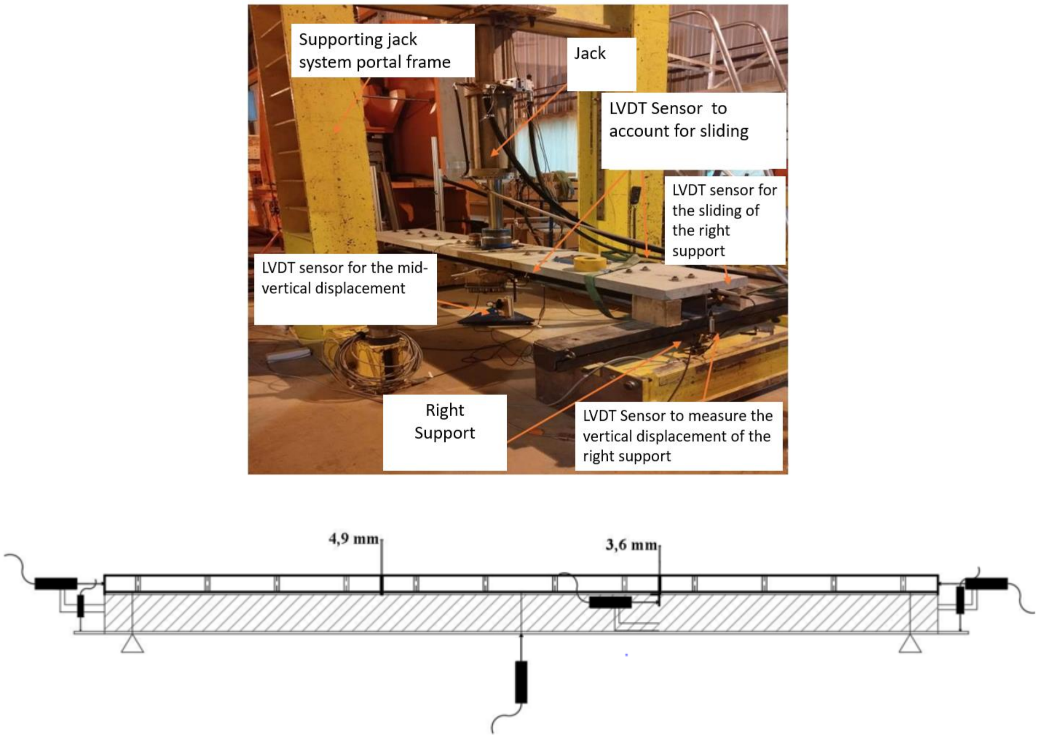

FIGURE 9. **3 points flexural test on the demountable beam set-up and positions of load sensors**

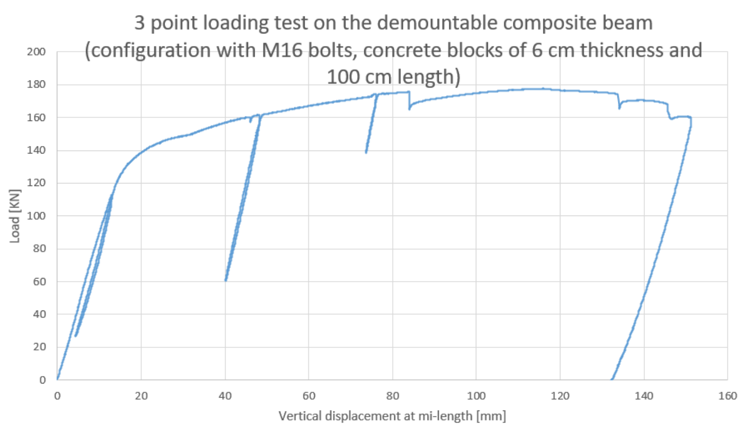

FIGURE 10. **3 points flexural test results: Load versus vertical displacement at beam mid-length**

B. Analytical solution and discussion

It is important to make sure that the proposed demountable solution works in a composite way, therefore we will compare the maximum load obtained experimentally to the one that should be obtained if we consider a perfect composite action of the structure according to Eurocode 4. Calculations show that the plastic neutral axis of the system is located at the upper steel beam flange. Therefore, during the test, concrete is only subjected to compression. A plastic moment calculation, shows that the plastic moment that can be supported by the composite beam is equal to 120.59 kN.m. which corresponds to a load of 172.3 kN. A plastic moment analysis of the HEA 160 steel beam alone, shows that it can sustain 125.3 KN. The additional strength observed is equal to 46.97 kN and can be related to the composite action of the steel beam and the concrete underlying slab. Experimentally, we obtained a maximum load equal to 177 kN, which is comparable to the theorical 172 kN load calculated by considering an elastic perfectly plastic behavior of the steel beam. The small difference that has been observed could be explained by the fact the real behavior of the steel beam is not linear perfectly plastic and that some strain hardening happens (which allows withstanding more load).

A numerical model is under development on Abaqus for the 3 point flexural test. The same material properties and contact interactions that were used to model the push out test will be used to model the flexure test. A pretention of the bolts equal to 55 kN will also be considered. The loading plate and supports will be modeled as steel elements having a linear behavior. The meshing of such model is shown in Figure 11.

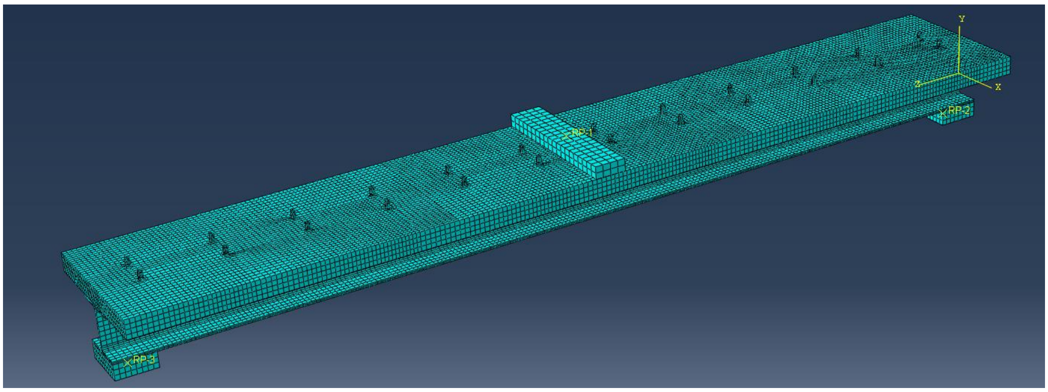

FIGURE 11. **3 point flexural test meshing**

Conclusions

In this paper, an original demountable concrete steel beam solution was presented. The behavior of the bolted connections used was studied through a push out test that was also modeled using Abaqus. The numerical model that was developed allows predicting well the maximum force attained during the pushout test. However, such model doesn't predict accurately the displacements of the system and is more stiff than the reality. The presented model should be improved in a way to account for the play that is possible in the reality within the holes where the bolts are put. It should also be improved by replacing the linear perfectly plastic law used for the bolts by a non linear law with damage. The 3 points flexural beam test that was performed on the demountable beam showed that it attained a composite behavior under the ultimate limit state. Other configurations are under study: different thicknesses, lengths, number of concrete blocks, different bolt sizes, *etc.* The idea is to try to come up with the best solution that allows reaching the higher capacity and that has a composite behavior while allowing demountability of the system. It is also necessary to study the behavior of the adopted solution under the serviceability limit state to make sure that it allows reaching reasonable deflections and vibrations for the users.

Acknowledgement

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