Effect of spacing between concrete blocks on the mechanical behavior of demountable steel-concrete floors under flexure

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Abstract This article explores an innovative solution for demountable and reusable composite structures made of concrete panel blocks bolted to a steel beam. This floor system was studied both experimentally and numerically under a three-point bending test. Results showed a good agreement between experimental test results and simulations. It is worth noting that in this type of solution, a full surface contact between concrete blocks cannot be achieved due to concrete manufacturing imperfections that make the surface of concrete blocks uneven. Such imperfections induce a certain spacing between concrete blocks that could affect the mechanical behavior of this solution especially under small displacement values (serviceability limit state). A parametric study on the influence of these spacings on the mechanical behavior of such demountable structure was conducted in this article.

Keywords Demountable beams, composite, concrete/steel, spacing, flexure.

I. INTRODUCTION

Composite structures imply combining different materials in a way to improve their individual properties to come up with structures having better mechanical and thermal characteristics. For instance, in the field of reinforced concrete, the combination of steel and concrete allows overcoming the weakness of concrete in tension through the addition of steel rebars. In civil engineering, composite structures are frequently non-demountable solutions (use of welded connectors to come up with a composite concrete/steel complex, use of shear connection between steel and concrete, such as welded headed studs that has been the subject of extensive studies, highlighting their effectiveness as structural connectors ([1], [2]), *etc.*).

To respond to the imperatives of sustainable development, particularly in the context of the adoption of the "RE2020" law [3], the development of demountable and reusable structural systems is emerging as a promising solution, offering flexibility and waste reduction [4]. In this regard, recent research articles evaluated the impact of the use of demountable bolted connectors to ensure a composite action between steel beams and concrete panels [5].

The aim of this research project is to explore an innovative, demountable solution in which concrete panel blocks are bolted to steel beams, allowing the reuse of materials, and offering significant advantages in terms of sustainability. Due to the imperfections induced by concrete manufacturing, making the surface of the concrete blocks uneven, a spacing between the concrete blocks is created which can impact the mechanical behavior of the composite floor.

As part of our research project, we conducted a three-point bending test on beams made of concrete panels attached to an HEA 160 steel beam, using M16 diameter bolts. This article highlights the experimental and numerical results obtained for a configuration with three concrete blocks, employing a connection with M16 bolts, concrete blocks having each a thickness of 6 cm, and a length of 100 cm [6]. Since the behavior of such structures depends on the spacing between concrete blocks, a sensitivity analysis was numerically performed to determine the spacing value that needs to be used numerically to best approximate the experimental behavior of the floor system. Such spacing was numerically varied in order to quantify to which extend it impacts the behavior of the structure.

The first part of this article focuses on describing the geometry and mechanical properties of the elements forming the studied floors. In the second section, experimental and numerical results obtained when performing a 3 point bending test on a composite floor made of 3 concrete blocks are provided. The third part deals with the impact of spacing between the concrete blocks on the mechanical behavior of the demountable composite steel/ concrete structure under study.

II. Geometry and mechanical properties

Due to observed defects in the manufacturing of the hot-rolled HEA160 section, flange and web thicknesses of our tested profiles were measured. Such measurements revealed significant deviations from the standard dimensions of an HEA160 section. Specifically, the flange thickness was measured as equal to 8.25 mm, while the web thickness was measured as equal to 6.6 mm, deviating from the usual standards of 9 mm for the flange and 6 mm for the web.

The steel used is considered homogeneous and isotropic, with an estimated density of 7850 kg/m^3 for all components. According to the NF EN1993 standard [7], the Poisson's ratio (ν) can be established as equal to 0.3 and the modulus of elasticity (E) as equal to 210 GPa. To assess the elastoplastic properties of the steel used, tensile tests were conducted on samples extracted from the studied HEA160 profile, providing the stress-strain relationship presented in Figure 1. M16 bolts were also tested to evaluate their yield stress and ultimate stress (mechanical elastic-plastic properties shown in Table 1).

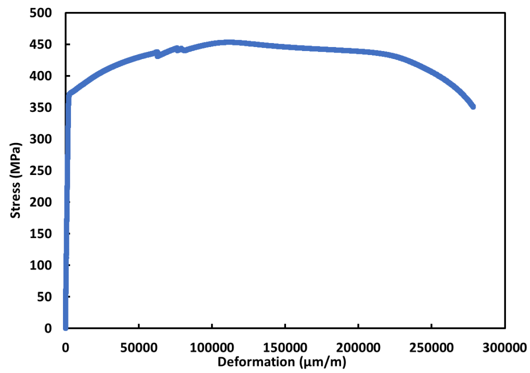

FIGURE 1. Stress versus strain evolution for a sample extracted from the HEA 160 beam subjected to tension

TABLE 1. Mechanical properties of the M16 bolts

Young Modulus (GPa)	Yield stress (MPa)	Ultimate stress (MPa)
205.90	922.60	982.40

The tested concrete panels were manufactured by a professional supplier. Cylindrical specimens made from the same concrete mix used to construct the concrete blocks were also produced by the same supplier, and then subjected to compression tests in accordance with the standards defined in NF EN 12390-3 [8]. These tests, conducted on three concrete specimens, allowed the determination of the Young's modulus of the concrete used and the definition of other concrete parameters. Concrete panels considered in this study have the mechanical properties indicated in Table 2, (average value obtained from three tests).

TABLE 2. Mechanical properties of the concrete blocks

Compressive Strength (MPa)	Young Modulus (GPa)	Tensile Strength (MPa)
34.2	32.8	3.5

Concrete behavior was modeled using the damage plasticity model in Abaqus. Stress, strain, as well as traction and compression damage evolutions, were calculated in MATLAB using the Model Code model [9] and implemented in Abaqus. These data were used as inputs for the concrete damage plasticity model in Abaqus and are presented in Figure 2.

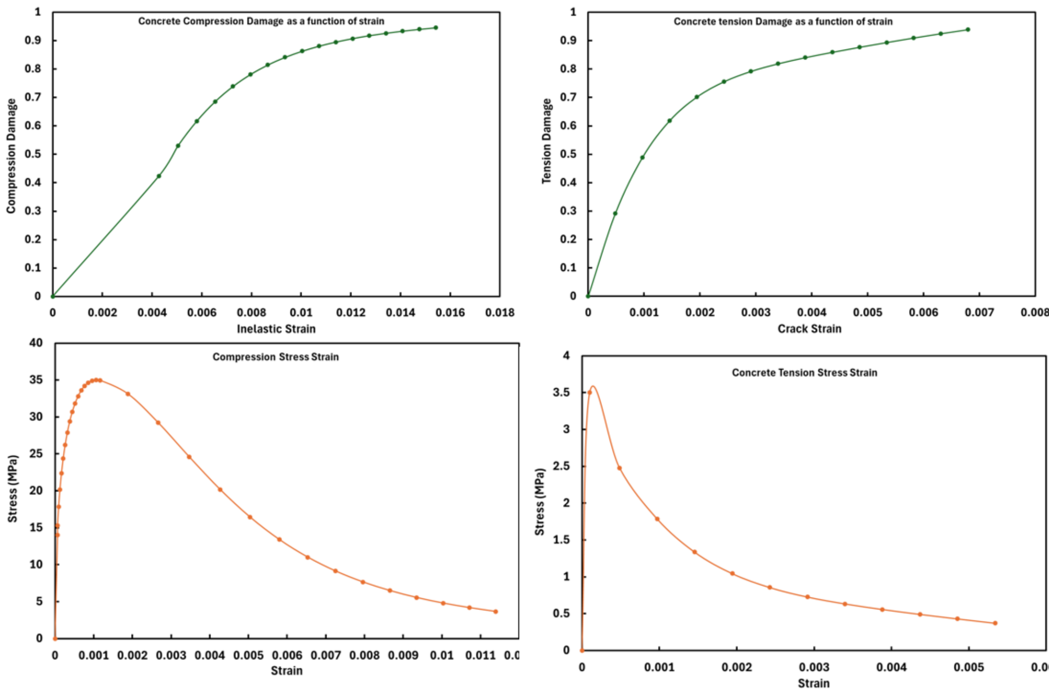

FIGURE 2. Constitutive Behavior of Concrete under Compression and Tension, [9]

III. Experimental and numerical results of a three-point bending test

A. Experimental Setup and Test Results

The tested steel/concrete floor is made of three concrete blocks measuring 50 cm by 100 cm. They are 6 cm thick and are attached to a 3 m long HEA 160 steel girder with M16 bolts, as depicted in Figure 3. This demountable beam was subjected to a three-point bending test to characterize its mechanical behavior. Seven displacement transducers (LVDTs) were positioned at specific vertical and horizontal locations on the composite beam. One LVDT was specifically dedicated to measuring the deflection at mid-span, while two others were positioned to assess the vertical displacement of the left and right supports. Two additional transducers were used to quantify the horizontal slip of the central block on both sides of the beam and the last two transducers were allocated to measure the slip at the ends of the beam, both left and right.

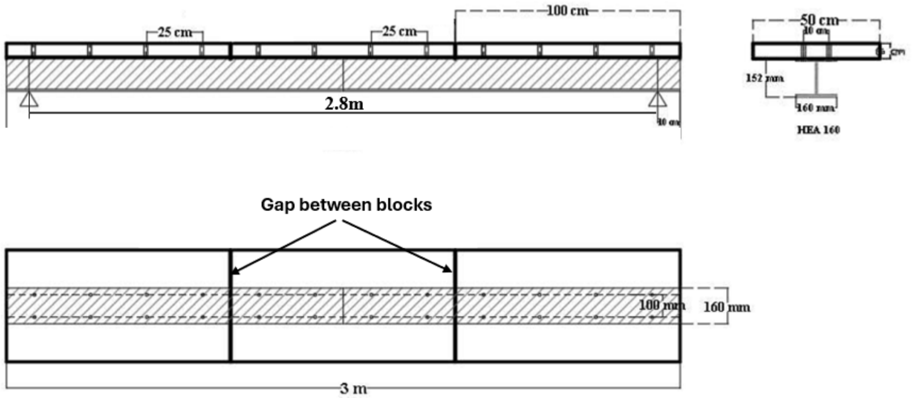

FIGURE 3. Geometry of the tested demountable composite concrete/ steel beam

The beam was subjected to static loading conditions until it failed. This test was conducted in several distinct phases. Initially, the beam underwent three cycles of loading and unloading, then the beam was loaded until failure. During the first cycle, a force of 110 kN was applied to assess the presence of slippage at the supports (phase a shown in Figure 7). Subsequently, upon reloading to a force of 120 kN, a curvature in the force-deflection curve at the midspan of the beam was observed, accompanied by a slight compression on the anti-skid wooden wedges beneath the right support slab (phase b, Figure 7).

At 160 kN, the load was reduced to 60 kN, followed by a reloading to assess stiffness evolution. This phase was marked by the appearance of a crack at the midspan of the central block, attributed to the compression of the concrete block and on a punching of the jack on the 50x20 cm plate (phase c, Figure 7). This phenomenon is shown in Figure 5.

The beam was then reloaded until failure at a force of Fpl = 171 kN. A force peak was observed at 174 kN, resulting in a small drop to 140 kN, followed by a reloading up to 174 kN (phase d, Figure 7). At a force of F = 178 kN a drop in force was observed, followed by a recovery (phase e of Figure 7). This drop was attributed to a significant degradation of concrete at the loading point, as shown in Figure 6.

Test results also indicate that the beam reached a maximum deflection at mid-span of approximately 115.8 mm. Experimental results are presented in Figure 7.

It can be observed that the demountable beam sustained a maximum load of 177.64 kN, which is comparable and very close to the value Fpl = 171.08 kN obtained by analytical elasto-plastic calculations with the assumption of a fully composite behavior, with a difference of 3.69 % [6]. During the bending test, the failure of the beam happened due to concrete crushing in the central block and due to the plastic deformation of the steel section, without bolts breaking. It should be pointed out that an additional three-point bending test was conducted on another HEA 160 steel beam, similar to the one used in the mixed concrete/steel structure. Such beam sustained a maximum load of 117 kN and a maximum displacement of 75 mm. This result demonstrates a significant improvement in load-bearing capacity and structural performance achieved through the inclusion of concrete blocks, highlighting the benefits of material synergy in composite construction (results are shown in Figure 9)

The stiffness of the beam increased during the loading process. Its value was evaluated during the 3 loading cycles previously presented as well as during the last loading phase. Beam stiffness value thus went respectively from a value of 9.091, to a value of 9.559, a value of 11.957, to reach a value of 13.010 kN/mm during the last loading phase. Such stiffness variation is due to the fact that during the loading process, initially existing gap between concrete blocks due to their uneven surface (induced by concrete manufacturing imperfections) is gradually reduced as concrete blocks enter into contact. During this process, the composite action of the beam increases as the different blocks start working together.

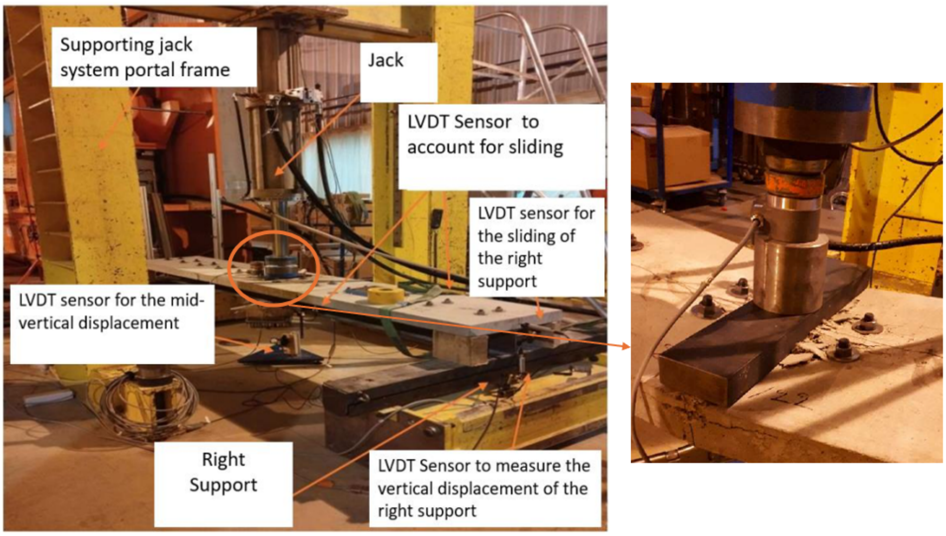

FIGURE 4. Experimental setup devices

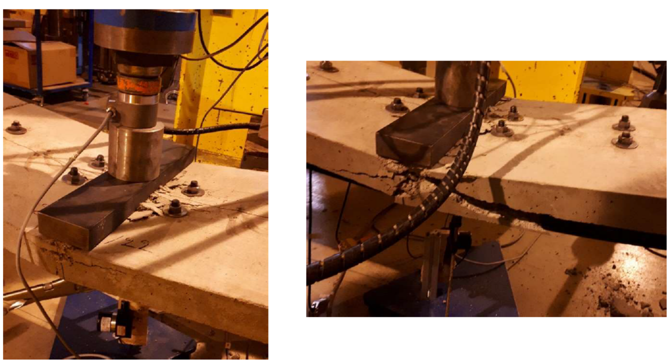

FIGURE 5. Crushing of the concrete central block due to cylinder punching, phase (c)

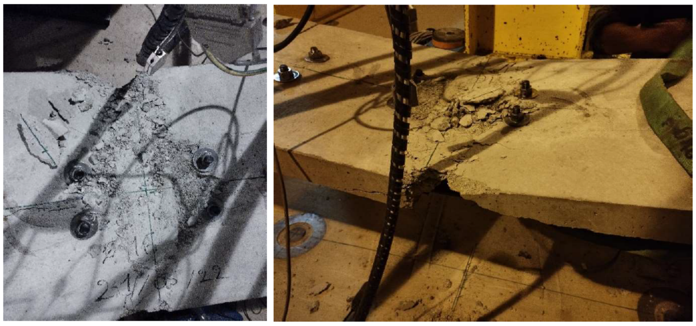

FIGURE 6. Crushing of the intermediate concrete block during phase (e)

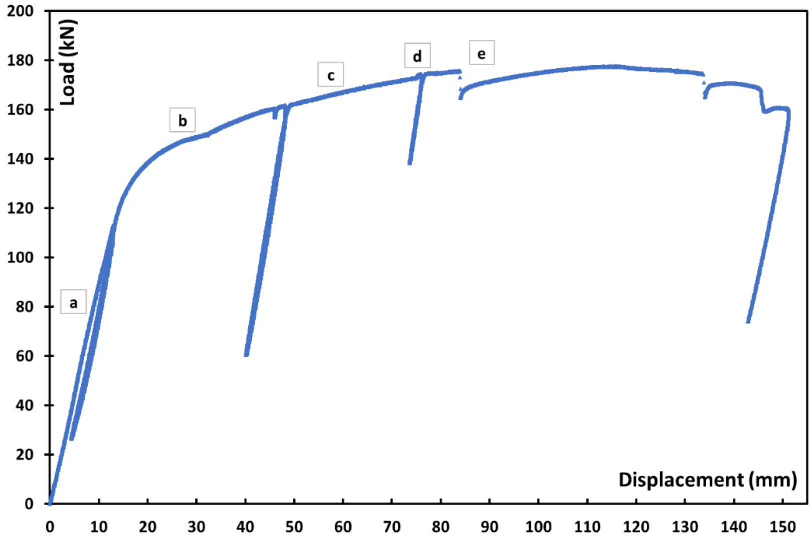

FIGURE 7. Results of the three-point bending test performed on the concrete/steel composite beam: load as a function of vertical displacement measured at midspan (letters a, b, c, d and e show the different loading and unloading cycles)

B. Numerical model and results

The 3-point bending test performed experimentally was modeled using the finite element analysis software Abaqus. The finite element model was validated by comparing the results obtained with the experimental ones.

A thorough study was conducted to assess the impact of element type and mesh refinement level on simulation results. Quadratic finite elements, as depicted in Figure 8, were chosen due to their ability to accurately represent complex curvatures and capture bending effects which is essential for modeling structures subjected to bending loads such as our composite beam. Additionally, a comprehensive sensitivity analysis study was carried out, where mesh size was varied until stable results were obtained. 20-node quadratic hexahedral elements (hex20), were thus finally used as in the study by Béreyziat et al. in 2022 [10] with a size of 20 mm.

Regarding the mesh presented in Figure 8, the finer mesh refinement around the bolts (size of 5 mm) is due to geometric considerations, while at the mid-support, it aims to ensure mesh regularity. The simulation was simplified by modeling only a quarter of the composite beam subjected to three-point bending. The input displacement value in Abaqus corresponds to the maximum observed deflection during the three-point bending test, which is 152 mm for a composite beam made of three concrete blocks and an HEA160 beam. External forces were applied directly to a reference point at the center of the load cell. This reference point can transmit reactions across the entire support surface, which in turn transfers the loads to the beam.

The modeling of interactions between different surfaces was conducted using the surface-to-surface contact feature available in the ABAQUS software, [11]. To ensure an accurate representation of mechanical stresses, the penalty contact method was chosen, which is well-suited for this type of application [12]. This approach was applied to all the interfaces of the model. More specifically, the HARD contact property was employed to describe contact behavior in the normal direction to the interface plane. Regarding the tangential contact, the PENALTY option was used, with an appropriate friction coefficient to model interactions.

A hard normal contact interaction was considered between the elements, along with a tangential contact with a friction coefficient of 0.2, in accordance with the NF EN 1993-1-8 standard [13].

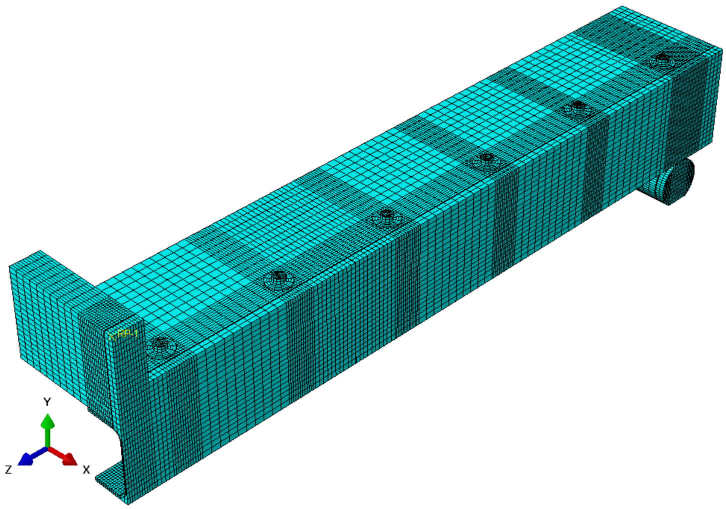

FIGURE 8. Mesh used to model the composite concrete/steel beam subjected to a 3-point bending test

Due to the uneven surface of the concrete blocks induced by manufacturing imperfections, a certain experimental spacing was observed between the different concrete blocks. Such spacing between blocks was accounted for in the numerical model (a spacing value e=0.5 mm was thus used numerically). Figure 9 illustrates the comparison between the force-displacement curve obtained numerically (with a spacing e=0.5 mm) and the one determined from the experimental test performed.

It can be observed in general that the numerical results align very well with the experimental findings. The stiffness of the numerical model is equal to 9.28 kN/mm, only 2.04% higher than the experimental value. Regarding the maximum force supported by the composite beam, numerically a force of 176.44 kN was obtained, which is 0.68% less than the experimental value.

Figure 10 illustrates the appearance of cracks between bolt rows and the crushing of the concrete central block during the 3-point loading test. Similarly, to what was observed experimentally, the numerical model shows the formation of s, longitudinal cracks along bolt rows (Figure 11) as well as concrete crushing of the intermediate block at mid-span, resulting from the compression of the concrete block and the punching of the jack on the plate.

Thanks to this comparison, we can affirm that the developed finite element model accurately replicates the mechanical behavior of the composite beam examined in this study.

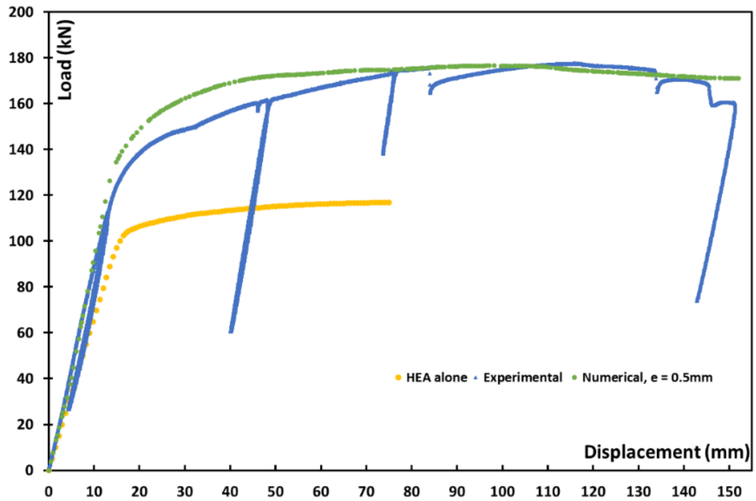

FIGURE 9. Comparison of numerical and experimental results (three-point bending test)

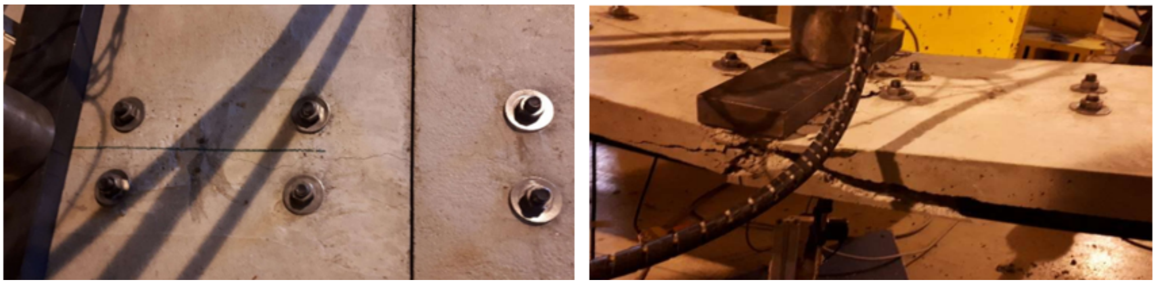

FIGURE 10. Cracks between bolt rows and crushing of the intermediate concrete block

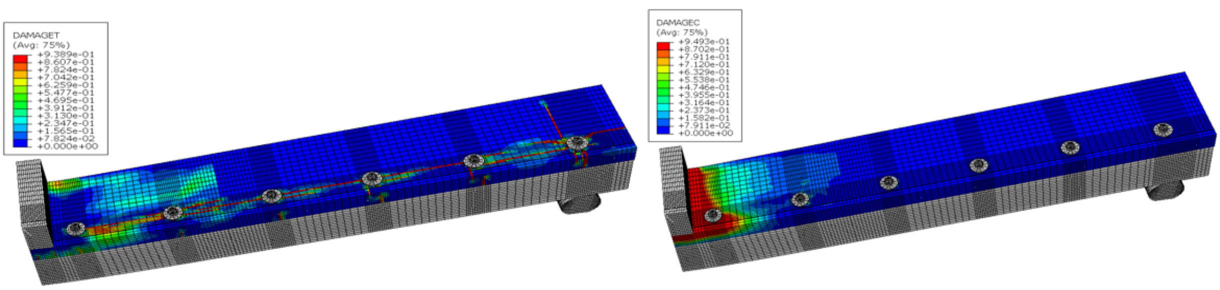

FIGURE 11. Numerical observation of cracks between bolt rows and crushing of the central concrete block

IV. Effect of spacing between concrete blocks

Using the developed finite element model, a design optimization study was conducted to evaluate the influence of spacing between concrete blocks on the mechanical behavior of the demountable composite beam presented in this article. Instead of simply presenting a sensitivity analysis, this study focused on finding the optimal spacing configuration to achieve targeted stiffness and strength. Five configurations were considered with different spacings (0 mm, 0.5 mm, 1 mm, 1.5 mm, and 2 mm).

Figure 12 illustrates the load-displacement curves obtained at mid-span for different spacing values.

The spacing between concrete blocks plays a crucial role in the stiffness of the structure. It is interesting to note that this spacing affects differently the mechanical behavior of the beam under serviceability limit state and under ultimate limit state. When the spacing between concrete blocks is smaller, there is generally a gain at the serviceability limit state (under small displacements). This means that the beam is less prone to excessive deformations or cracks under normal loading conditions (the beam has a higher initial stiffness and the composite action is improved).

However, it is important to note that a reduced spacing does not necessarily result in a gain in terms of the maximum strength of the beam. When the maximum load is applied, both the steel and concrete elements work synergistically until they reach their ultimate limit. Indeed, at this loading stage, concrete blocks are already in contact, which increases the stiffness of the beam significantly, allowing a full composite behavior (for an important loading, the initial spacing between blocks is equal to zero since the different blocks come into contact).

Table 3 presents a detailed comparison of the stiffness and maximum load values obtained using the numerical model on the demountable steel-concrete composite beam, considering various spacings between the blocks.

Results show that the model with a spacing of 0.5 mm between the blocks stands out as the one closest to the experimental findings.

It is interesting to note that, in the case of demountable composite structures, it is important to avoid gaps between prefabricated concrete panels during the assembly of the beam or to fill the spaces with mortar or resin (better option to ensure dismantlability) to maximize the performance of the composite beam under the serviceability limit state.

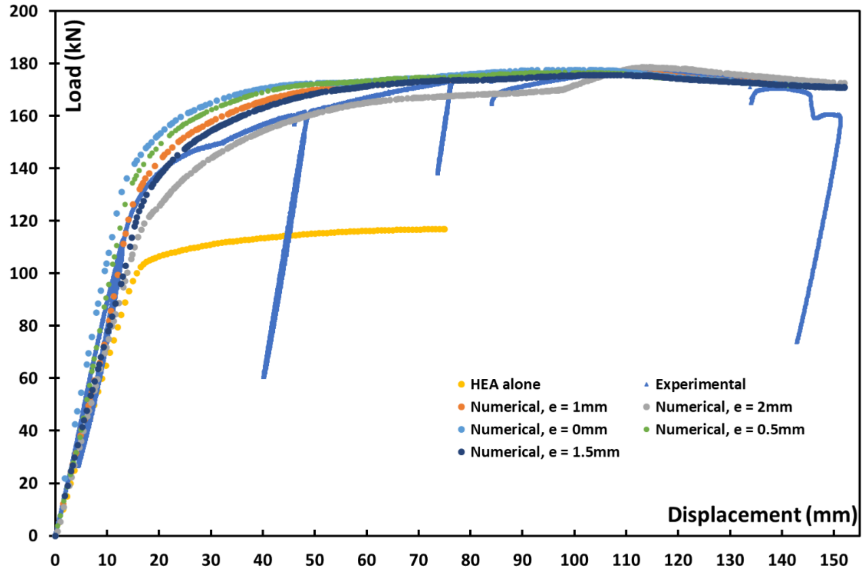

FIGURE 12. Effect of the spacing between concrete blocks on the force-displacement curve

TABLE 3. Effect of the spacing between concrete blocks on the stiffness and maximum force of the steel-concrete composite beam

Spacing	Initial stiffness (kN/mm)	Deviation from experimental data	Maximum Force (kN)	Deviation from experimental data
2 mm	7.42	17.65 %	178.60	0.54 %
1.5mm	7.59	15.76 %	175.58	1.15 %
1mm	7.72	13.05 %	176.32	0.74 %
0.5mm	9.28	2.04 %	176.54	0.62 %
0mm	10.00	9.90 %	177.57	0.04 %

IV. Conclusions

The study on the mechanical behavior of demountable steel-concrete composite beams under bending provides valuable insights into the effect of spacing between concrete blocks on the overall performance of the structure. The innovative use of concrete panel blocks attached to steel beams offers a promising solution for demountable and reusable composite structures, thereby addressing sustainability and waste reduction requirements in the construction industry.

This type of demountable composite structure is sensitive to the spacing between the blocks, which affects the initial stiffness of the structure but not its maximum loading capacity. To increase this initial stiffness and improve the mechanical behavior of the beam at the serviceability limit state, it is necessary to reduce the spacing between the blocks. Up to a spacing of 0.5 mm, the loss of initial stiffness compared to a case with zero spacing between the blocks (e=0 mm) is not very significant, around 7%. Beyond this spacing, the gap reaches 20%. Due to imperfections on the contact surfaces between concrete blocks, induced during concrete manufacturing process, achieving zero spacing experimentally is difficult and some spacing remains between concrete blocks. Therefore, to develop this type of demountable structure, it is necessary to add demountable joints, such as resins, between the blocks to reduce this spacing.

All in all, obtained results in this study are interesting as they allow paving the way for future studies aiming to maximize capacity while allowing system disassembly in a way to develop sustainable structures that are both demountable and fully composite.

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