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# Evaluation of the Structural Behavior of Composite Slim-Floor Beams with Openings in the Web †

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**Abstract:** In this study, the bending behavior of Slim-Floor beams was analyzed using FE models developed in the ABAQUS software. The validity of these models was demonstrated by comparing the numerical results obtained with experimental data found in the literature. Through parametric evaluations, the following findings were verified: (i) the connection mechanisms adopted (concrete dowels, reinforcing steel bars, and adherence) were able to activate the composite behavior between steel and concrete; (ii) the spacing between the openings, the number of openings, and the diameter of the reinforcing steel bars determine the behavior of the connection; (iii) adherence contributes little to the strength of the connection, and therefore, its contribution can be neglected; (iv) the connection mechanisms adopted in this study can promote the ductile behavior of the Slim-Floor beams.

**Keywords:** Slim-Floor; composite beam; connection mechanisms; concrete dowels; reinforcing steel bar; adherence

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## 1. Introduction

Conventional composite floor systems are formed by steel beams and concrete slabs positioned on the steel profile. In these systems, the composite behavior between steel and concrete is activated using mechanical shear connectors (stud bolts, Perfobond [1], Crestbond [2], and others) that are placed in the upper flange of the steel profile. A Slim-Floor is a flooring system that combines steel beams and slabs integrated into the structure, resulting in a significant reduction in the overall floor height [3]. This allows for a more efficient design, making construction easier and saving space. Despite these advantages, the use of mechanical shear connectors in the steel profile is not feasible, as the concrete layer above the steel is not thick enough for these connectors to work properly. Thus, over the last few years, several studies [3–6] have been carried out to develop composite mechanisms capable of "activating" the composite behavior between steel and concrete in Slim-Floor systems.

The first Slim-Floor systems used the adherence formed between steel and concrete as a connection mechanism. In some situations, as in the case of the Slimdek system [7], this mechanism was improved by introducing ribs in the upper flange of the steel profile. However, in all instances, these connection mechanisms led to undesirable collapse modes. To overcome this problem, Braun et al. [6] proposed the introduction of openings in the upper region of the steel profile web. In this way, the composite behavior between steel and concrete was activated using three connection mechanisms: (i) concrete dowels, (ii) steel reinforcement bars, and (iii) adherence. In this context, the present study seeks to evaluate the structural behavior of Slim-Floor beams with openings in the web using FE models.

## 2. Materials and Methods

### *2.1. Development of the FE Models*

The FE models presented in this study were developed using the modeling methodology proposed by Paes [3], taking into account the experimental conditions, geometric characteristics, and mechanical properties presented by Braun et al. [6].

#### 2.1.1. Geometry and Structural Characteristics of Experimental Prototypes

Braun et al. [6] experimentally analyzed the structural behavior of four prototypes called B1, B2, S1 and S2. All prototypes were manufactured using HEM 220 profiles, to which a 20-mm-thick steel plate was welded (Figure 1). This profile was integrated into a composite slab concreted in situ, formed by steel decks and rock wool blocks.

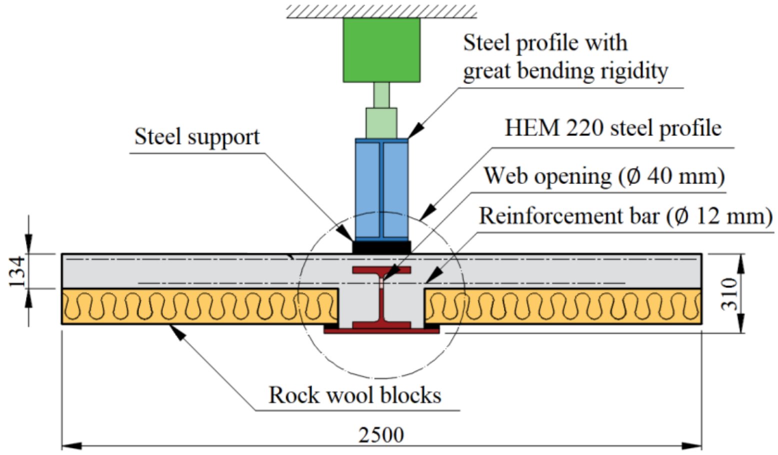



**Figure 1.** Geometric characteristics of the prototypes B1, B2, S1 and S2 experimentally tested by Braun et al. [6].

The structural configuration of these tests corresponded to a double-supported beam with a span equal to 8000 mm for prototypes B1 and B2, and 4000 mm for prototypes S1 and S2. All prototypes utilized the three aforementioned connection mechanisms. However, in prototype S2, some openings were filled with a low-stiffness material to prevent the formation of concrete dowels in these regions (Figure 2).

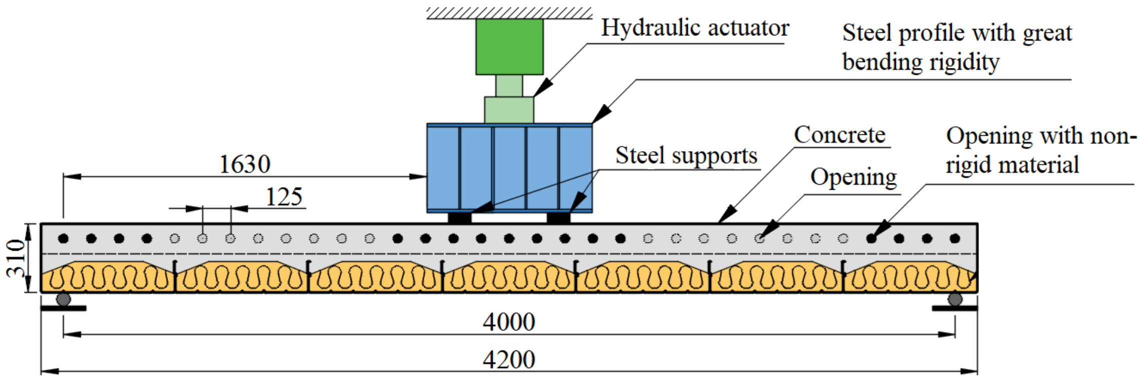



**Figure 2.** Structural configuration used by Braun et al. [6].

2.1.2. Considerations about the FE Models

The FE models were discretized using elements of the solid type C3D8, C3D6, applied in the regions that represent the steel profile and the concrete slab (Figure 3), and B31, applied in the regions that represent the reinforcement bars. In all cases, the maximum dimension of the finite elements was equal to 25 mm, a value defined after carrying out mesh tests. Following the methodology proposed by Paes [3], we chose to disregard the contribution of rock wool blocks.

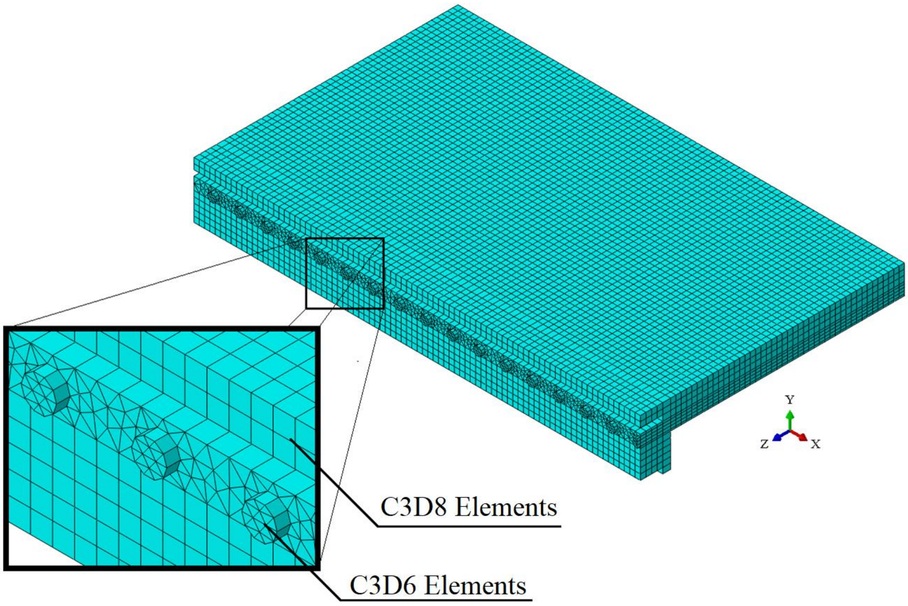



**Figure 3.** Mesh used in FE models and detail of the opening region (concrete dowel).

The mechanical behavior of steel and concrete were simulated using the Plasticity and Concrete Damaged Plasticity models, respectively. Adherence was simulated using CONN3D2 type connection elements distributed between some nodes of the steel profile and the concrete slab (Figure 4). The translational movement of these connection elements was defined by the Slide-plane option, which allows the translation of the connected nodes along the local axes U2 and U2 and prevents movement along the local axis U1.

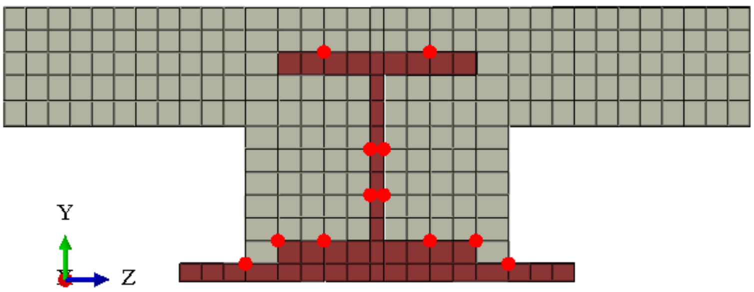



**Figure 4.** Distribution of connecting elements along the cross section of the FE model.

*2.2. Parametric Study*

The parametric study associated with the connection mechanisms seeks to evaluate the influence of concrete dowels, reinforcement steel bars and adherence on the structural behavior of Slim-Floor beams. In this way, the FE models presented in Table 1 were analyzed. These FE models were developed using the modeling methodology presented in Section 2.1.

**Table 1.** Connection mechanisms considered in FE models.

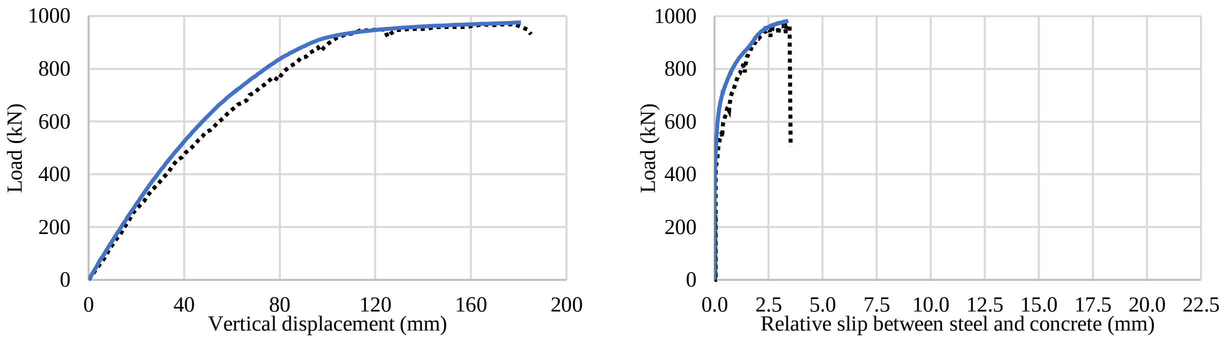
| Models | Connection Mechanisms |
| --- | --- |
| MC-M1-L8-IC | Complete interaction (no relative slip between steel and concrete) |
| MC-M2-L8-SI | No interaction (steel beam and concrete slab are considered isolated) |
| MC-M3-L8-PBA-RF | Three connection mechanisms: concrete dowel, reinforcing bars and adherence |
| MC-M4-L8-PA | Two connection mechanisms: concrete dowel and adherence |
| MC-M5-L8-PB | Two connection mechanisms: concrete dowel and reinforcing |
| MC-M6-L8-A | One connection mechanism: adherence |

## 3. Results and Discussion

### *3.1. Validation of the FE Models*

The modeling methodology presented in Section 2.1 is validated by comparing the load vs. deflection and load vs. relative slip curves obtained numerically with experimental ones presented by Braun et al. [6]. These results are shown in Figure 5, where the solid blue lines represent the results obtained through numerical simulations, while the dotted black lines correspond to the results obtained experimentally.

Analyzing the results presented in Figure 5, it can be seen that there is a good agreement between the results obtained using the FE models and the experimental results found by Braun et al. [6]. This observation indicates that the FE models developed were capable of representing a series of phenomena that occur in the Slim-Floor composite beam until it reaches collapse, such as: concrete cracking, steel yielding, transfer of forces between the reinforcing bar and the concrete, the confinement of the concrete dowel in the openings, and the slipping of the steel-concrete interface. The divergences observed between the numerical and experimental results can be attributed to four factors: (*i*) the difficulty of accurately characterizing the real behavior of the concrete in tension; (*ii*) the *Embedded* constraint used to simulate the adherence between the steel reinforced bars and the concrete; (*iii*) the difficulty in accurately simulating the mechanical behavior of the steel-concrete interface; and (*iv*) residual stresses introduced into the profile and steel plate during the manufacturing process. In general, the well agreement between the experimental results and the results obtained by FE models at all load levels allows us to assert that the numerical simulation methodology used is valid for representing the structural behavior of Slim-Floor beams with openings in the web.




(**a**) (**b**)

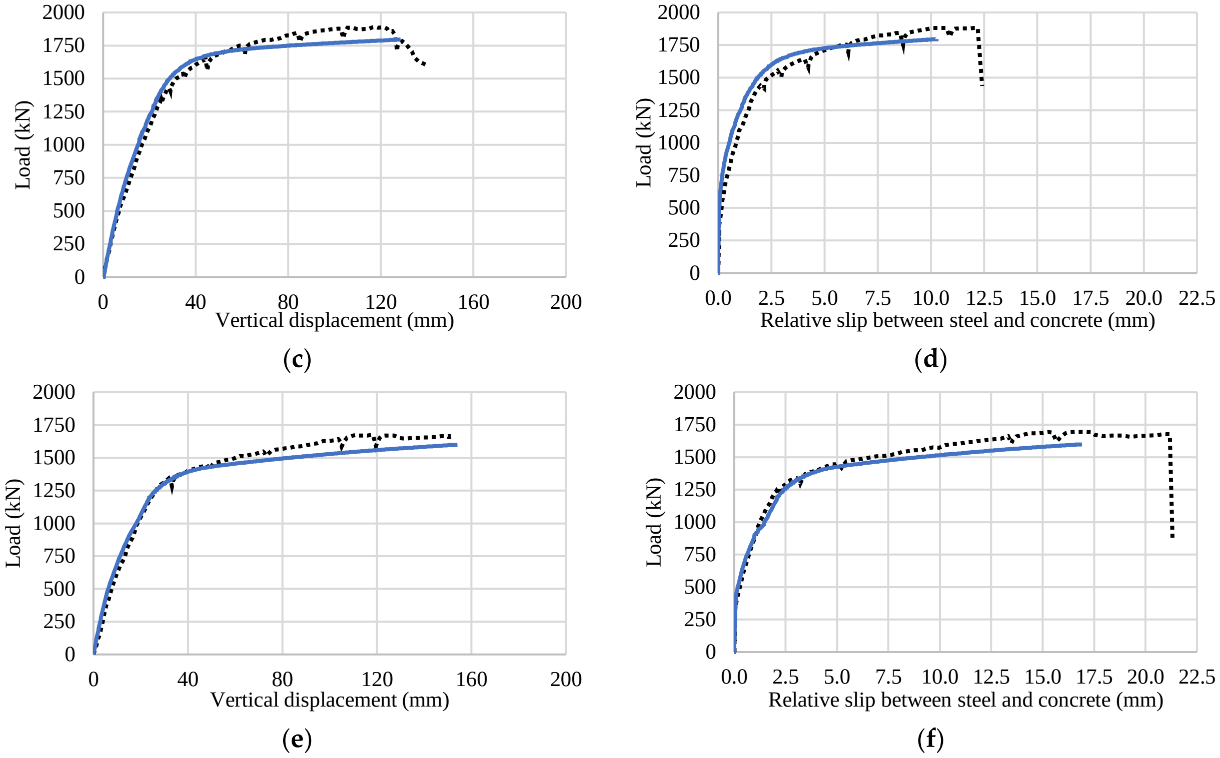



**Figure 5.** Comparison between experimental (dotted black lines) and numerical (solid blue lines) results. (**a**,**b**) prototypes B1 and B2; (**c**,**d**) relative load vs. slip results of prototype S1; and (**e**,**f**) prototype S2.

### *3.2. Influence of the Connection Mechanisms*

The influence of connection mechanisms can be analyzed through the load vs. vertical displacement curves shown in Figure 6. Based on these results, we can observe that the structural response of the reference model (MC-M3-L8-PBA-RF) is equal to the response of the model with full iteration (MC-M1-L8-IC). This observation demonstrates that the connection mechanisms used are capable of transferring all the shear forces that occur at the steel-concrete interface. Therefore, in this case, the resistant bending moment is controlled by the mechanical resistance of the steel or concrete sections, which implies a situation of complete interaction.

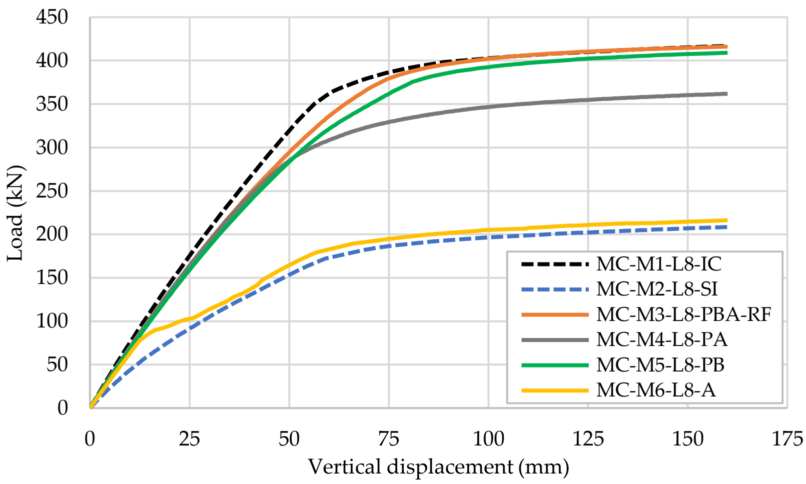



**Figure 6.** Load vs. vertical displacement curves obtained from FE models with different connection mechanisms.

These results also demonstrate that reinforcing bars are an important connection mechanism. Comparing the result of the reference model with the result of the model that does not use reinforcement steel bars (MC-M4-L8-PA), it can be seen that the maximum load reached by the reference models is approximately 15% greater than the load maximum obtained by models that do not use reinforcing steel bars.

On the other hand, the contribution of the adherence under collapse conditions is not significant. Comparing the result obtained by the model that does not use the adherence (MC-M5-L8-PB) with the result of the reference model, it can be seen that the maximum load achieved by the reference model is approximately 3% higher than the maximum load obtained by the model that does not consider adherence. Analyzing the result of the model that uses only adhesion as a connection mechanism (MC-M6-L8-A), it can be seen that this connection mechanism produces brittle behavior. Until reaching the maximum shear stress, the Slim-Floor beam behaves like a composite steel-concrete beam, and, after that point, it behaves similar to a steel-concrete beam without interaction (MC-M6-L8-SI).

## 4. Conclusions

This present study presented an evaluation of the structural behavior of Slim-Floor composite beams with openings in the web. For this, FE models were developed using the ABAQUS software and validated using the experimental results obtained by Braun et al. (2014). Using the modeling methodology validated, a parametric study was carried out which allowed the following conclusions to be reached: (*i*) the connection mechanisms adopted (concrete dowels, reinforcing steel bars, and adherence) were able to activate the composite behavior between steel and concrete; (*ii*) adherence contributes little to the strength of the connection, and therefore, its contribution can be neglected; and (*iii*) the connection mechanisms adopted in this study can promote the ductile behavior of the Slim-Floor beams.

**Author Contributions:** Conceptualization, L.C.M. and J.L.R.P.; methodology, L.C.M. and J.L.R.P.; validation, L.C.M. and M.G.M.; formal analysis, L.C.M.; investigation, L.C.M. and M.G.M. writing—original draft preparation, L.C.M.; writing—review and editing, M.G.M. All authors have read and agreed to the published version of the manuscript.

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