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Vertical load distribution in precast hollow core floors: State of the art and future perspectives

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Abstract

Precast prestressed hollow core (HC) floors are widely used in various applications within the construction sector. Such floors are usually designed as single, simply supported elements, although it is known that individual elements forming the floor interact with each other. This article presents the state of the art regarding load redistribution in HC floors in the light of experimental data, current analytical models and code provisions. While this phenomenon is widely known and recognized, only sparse, and often poorly documented experimental data are available, which represent the basis for the assessment and calibration of analytical models. Moreover, even though the available models and code provisions share similar assumptions, their outcomes are in some cases conflicting. Having recognized the existing knowledge gap, the authors outline future perspectives for the development of consistent analytical and numerical approaches supplemented by new experimental data.

KEYWORDS

hollow core slabs, load distribution, precast concrete, precast concrete floors, prestressed concrete

1 | INTRODUCTION

Precast prestressed hollow core (HC) slabs are widely used to construct floors in various applications within the building sector. Presence of cores largely reduces material consumption, which is further decreased since only longitudinal prestressing strands are used to reinforce the elements. This, together with quick assembly process and further possibility to reuse the elements,[1] makes using HC slabs sound from a sustainability perspective.[2]

Hollow core floors are usually designed for vertical loads, assuming that each unit can be treated as a single, simply supported element able to withstand the full effects of the imposed load, being therefore subjected to bending and shear. However, this approach is only valid for floor fields with regular shapes, subjected to uniformly distributed load and unaffected by openings. It is indeed common to see floors with large openings, as well as floors subjected to point or line loads acting on individual units. In such cases the elements forming the floor can be assumed to interact with each other, due to the presence of cast on site joints, and to the torsional stiffness of individual units. This phenomenon can be simply explained by assuming that longitudinal joints behave as rotational hinges, able to transfer shear forces only. Therefore, a portion of the applied load is transferred to adjacent units, thus reducing the amount of load carried by the directly loaded element.[3,4] Apart from the load reduction on the directly loaded element, the system effect due to the restraints and to the additional confinement that is imposed by adjacent slabs and by surrounding structural elements positively contributes to the bearing capacity of the floor. Therefore, a hollow core slab considered as part of a floor can, in certain scenarios, withstand higher loads at ultimate limit state (ULS) compared to the load withstood by a single isolated unit.

The aim of this study is to present the state-of-the-art knowledge regarding the above-mentioned topic in terms of experimental data, analytical models, and code regulations. Although there is evidence that numerical models can effectively predict the response of HC floors,[5–11] they are outside of the scope of this study, and are not dealt with. The fact that most of the experimental research on load distribution in HC floors was conducted between 20 and 50 years ago on units produced with materials, technologies and geometries typical of the time, causes a number of limitations in the application of computational methods developed back then. In addition, most of the existing analytical models in standards and literature are characterized by misspecifications and inaccuracies. There is therefore a need for a renewed recognition of this issue in modern HC floors, which would allow for a more optimized design, contributing to a sustainable development of the construction sector.

2 | MOST IMPORTANT EXPERIMENTAL STUDIES UP TO DATE

2.1 | Experimental investigations on vertical load redistribution in HC floors

While much attention has been paid to experimental studies on single HC units, among others in references 12–25, a limited number of experiments were carried out on full scale HC floor assemblies in which load distribution could be observed. The limited amount of full-scale test stems mostly from the scale of such experiments, which makes their execution complex and cumbersome in relation to common laboratories' facilities. Table 1 summarizes the experimental programs on HC floors, in which load distribution among units could be observed.

TABLE 1 Summary of the experimental studies on load distribution on HC floors.

Experimental program	Year	Span (mm)	Depth (mm)	Span to depth ratio (−)	Number of slabs in the floor	Slab width (mm)	Presence of openings	Type of applied load
LaGue, Setup 1[26]	1971	7620	200	38.10	7	600	Y	Distributed (S)
LaGue, Setup 2[26]	1971	7620	200	38.10	6	600	Y	Distributed (S)
Johnson and Ghadiali[27]	1972	7010	152	46.11	4	1016	Y	Distributed (S) (F)
Lejeune and De Niet[28]	1977	6000	200	30.00	6	1200	N	Line (S) (F)
Pfeifer and Nelson[29]	1983	13,500	305	44.26	4.5	2400	N	Line (S)
RAT01735/90, VTT[30]	1990	6500	265	24.53	8	1200	Y	Distributed (S) (F)
RAT12538, VTT[31]	1991	12,000	400	30.00	6	1200	N	Point (S) (F)
RAT12503, VTT[32]	1991	6000	400	15.00	4	1200	N	Point (S) (F)
Pajari[33]	2002	7000	400	17.50	4	1200	N	Point (S) (F)
Pajari[34]	2003	7000	200	35.00	4	1200	Y	Point (S) (F)
Zając et al.[35]	2021	6000	150	40.00	10	600	N	Distributed (S)

Note: (S): Serviceability conditions, elastic response—limited load intensity; (F): Failure conditions, load increased till failure.

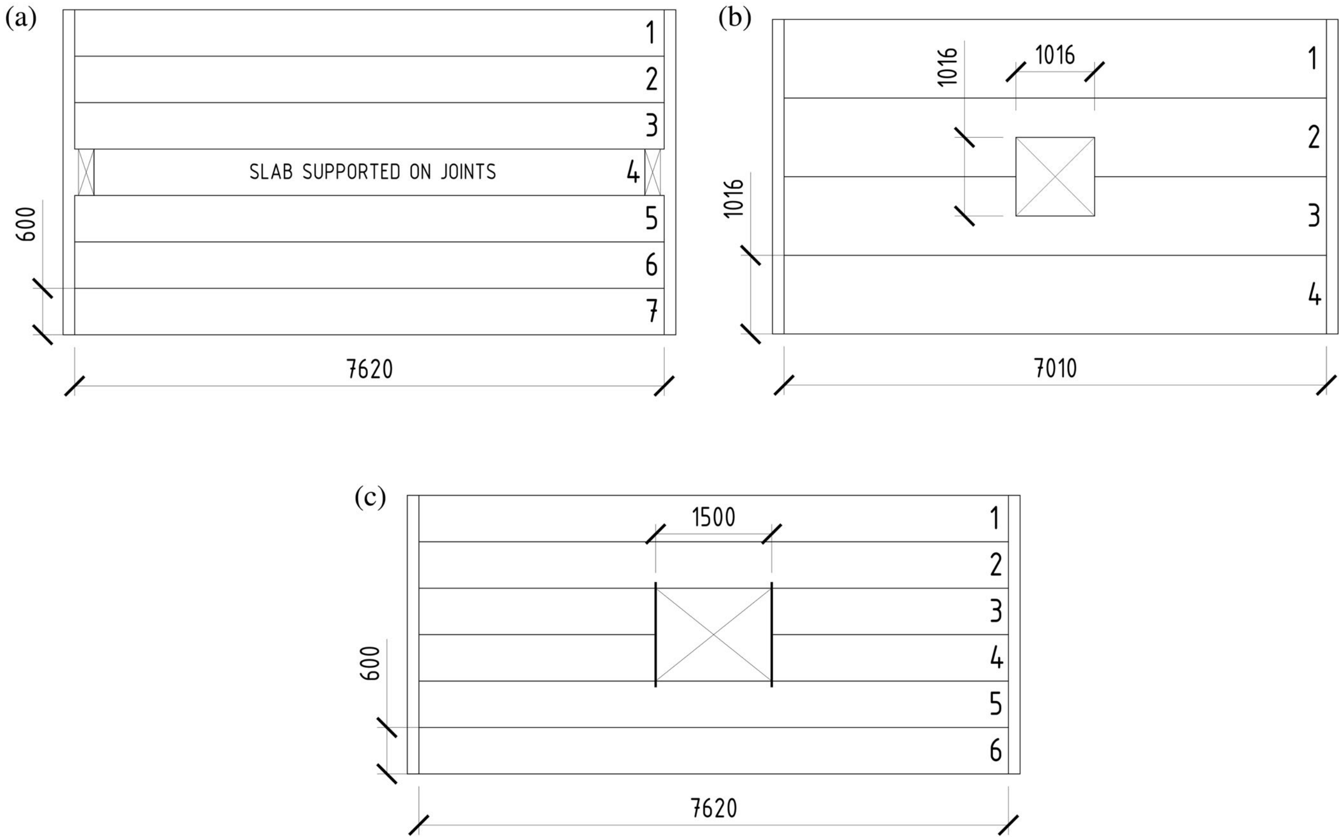

FIGURE 1 Sketch of the test setups investigated by LaGue (a, b) and Johnson and Ghadiali (c). *Source*: Adapted with permission.[26,27]

Behavior of HC floors with openings was first studied by LaGue[26] and Johnson and Ghadiali[27] at the beginning of the 70s, see Figure 1. Neither failure nor significant cracking was observed in setup 1 (Figure 1a) even though the floor was subjected to a distributed load equal to the theoretical limit, except for the unsupported slab, which was loaded up to 74% of that load. Similar observations were noted in setup 2 (Figure 1b). In setup reported on Figure 1c, despite the opening presence, the flexural failure was caused by a distributed loading that was 20% higher than the theoretical value.

Lejeune and De Niet[28] investigated the behavior of a HC floor subjected to linear loading, applied through two short spreader beams (Figure 2a). Several loading positions across the floor were tested (Figure 3a, P4–P6) with each slab being loaded individually; failure load was investigated by applying the loads at the center of the floor, directly over the joint between units 3 and 4 (Figure 3b). Floor failed under an applied load almost 4 times higher than the one leading to the collapse of a single element; a brittle failure mode was observed in the floor, compared to the ductile behavior of the single element (Figure 2b). The HC floor investigated by Pfeifer and Nelson,[29] see Figure 3a, was loaded with 4 point-loads along the span. The loads were first applied on the single units and the corresponding deflections and strains were measured. After unloading, grouting of the joints was performed, and loads were reapplied individually on each slab. These last tests showed that the joints were able to distribute the loads effectively, involving mainly two to three elements, and that the distribution width ranged from 36% to 54% of the span. A HC floor with a large opening was investigated in 1990 in the Finnish VTT laboratory,[30] as depicted in Figure 3b. The slabs forming the opening, which were supported on a cast on site concrete trimmer beam anchored into the cores of adjacent units, were loaded by an array of point loads applied through a system of spreader beams. A shear failure occurred in the slab adjacent to the opening (slab 7, see Figure 3b). A failure load corresponding to a distributed load of 28 kN/m^2 was reported, which was significantly higher than the usual load of 2 kN/m^2 adopted in case of residential buildings, for which such floors were usually provided for.

Two tests on 400 mm deep HC floors subjected to point loads were carried out in VTT,[31,32] see Figure 4. Load cells were placed between the supporting beams and HC elements to measure the support reactions. Several loading cycles under serviceability conditions were performed first for each considered loading position. Then the loads were

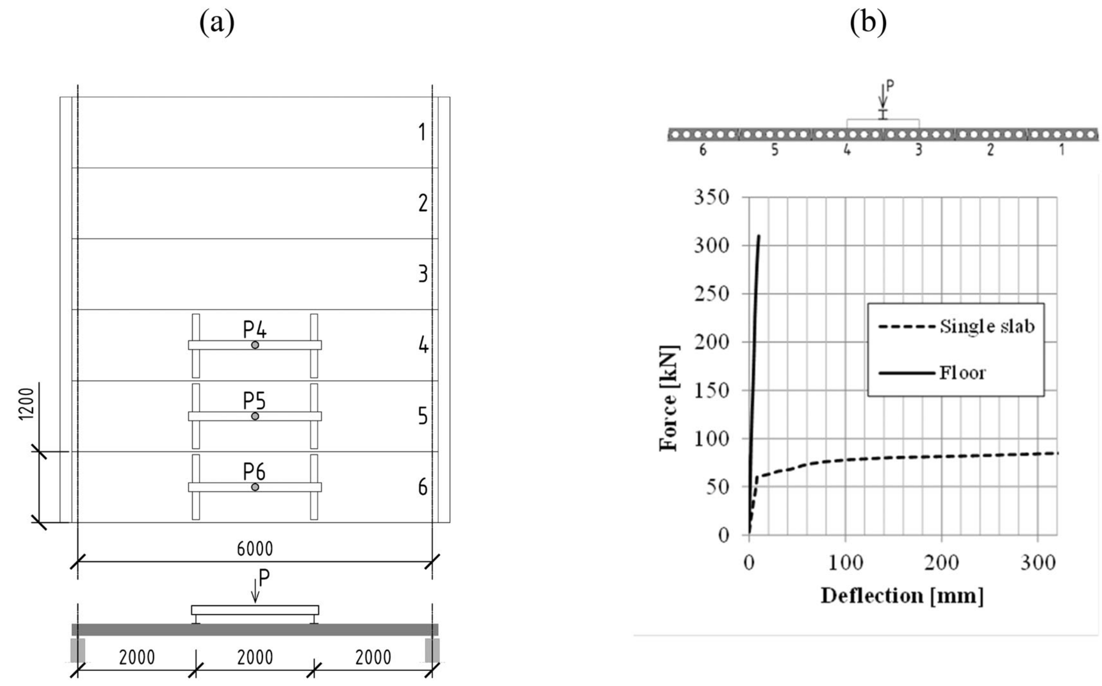

FIGURE 2 (a) Test setup adopted by Lejeune and Niet[28]; (b) Experimental load displacement curves up to failure obtained from tests on the floor and on a single unit. *Source*: Adapted with permission.[28]

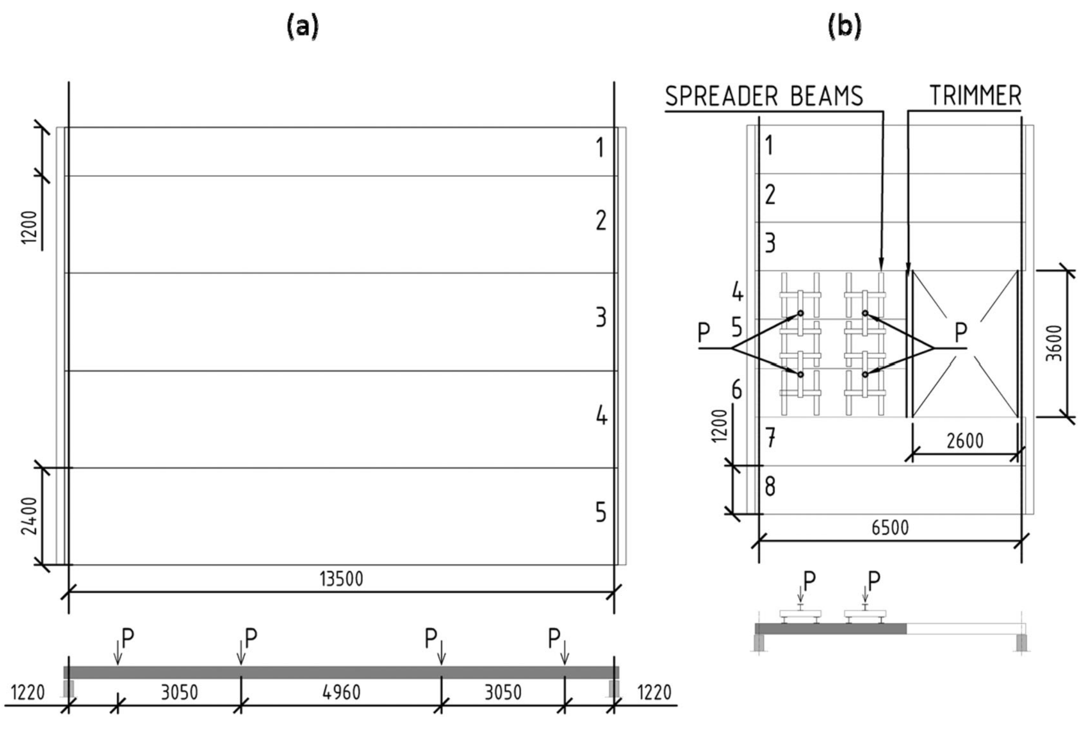

FIGURE 3 (a) Test setup by Pfeifer and Nelson[29]; (b) Test setup of a floor with a large opening supported on a concrete trimmer beam.[30] *Source*: Adapted with permission.[29,30]

increased up to failure, in two different loading positions—P4 and subsequently P2 in the 12 m long floor, P2 in the floor with the shorter span. A brittle punching failure was reported in both tests, anticipated by the appearance of longitudinal cracks on both top and bottom surfaces. No comparison with a single element test was provided, an estimation of load distribution in these experiments was performed in references 36,37.

The 400 mm deep HC floor depicted in Figure 5a was the object of the research on shear–torsion interaction

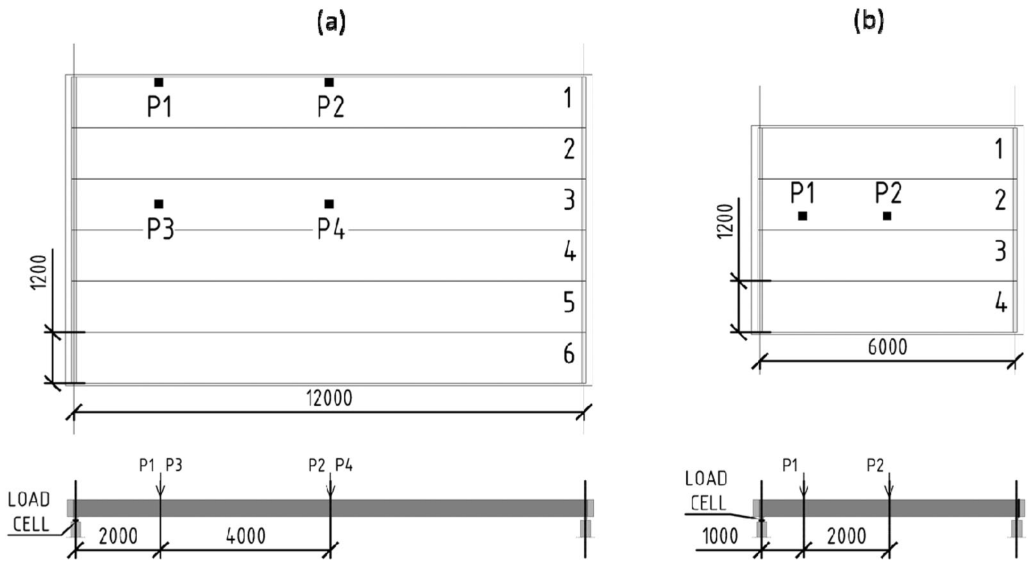

FIGURE 4 Finnish point load distribution tests: (a) 12 m long floor[31]; (b) 6 m long floor.[32] *Source*: Adapted with permission.[31,32]

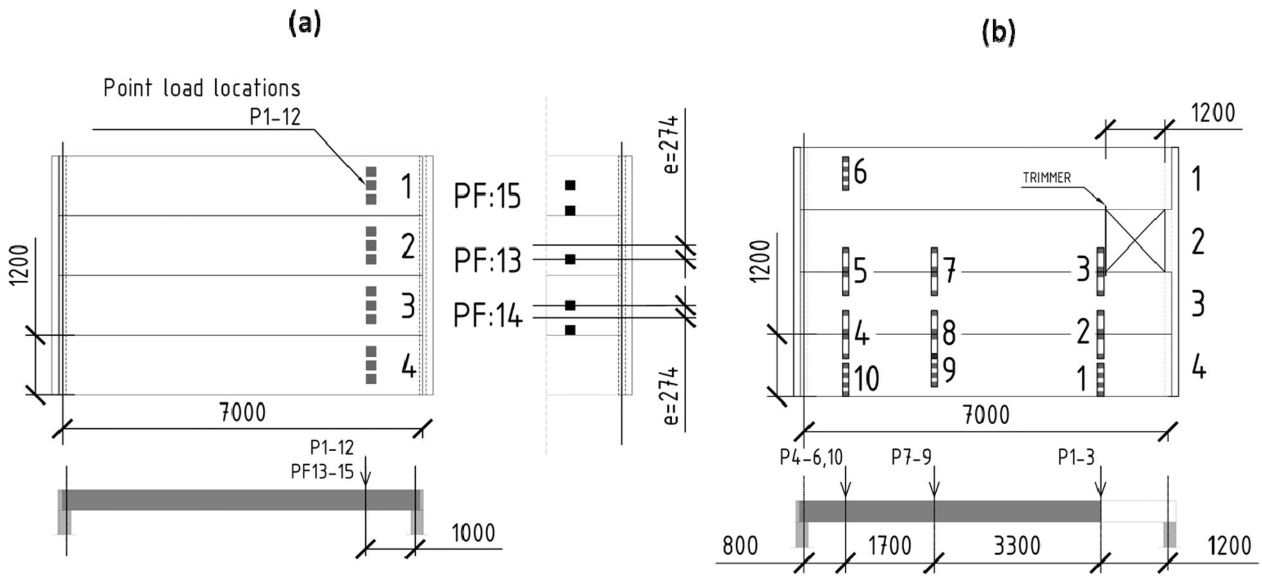

FIGURE 5 Load distribution tests[33,34] on (a) 400 mm floor, (b) 200 mm floor with opening. *Source*: Adapted with permission.[33,34]

performed by Pajari.[33] Longitudinal joints were pre-cracked. During each test, the floor was subjected to a single point load, whose position in the transverse direction was varied according to Figure 5a. The first 12 tests were carried out under serviceability conditions, and then three additional tests were also performed up to failure, by considering the loading arrangements PF13, 14 and 15. In PF13 a single point load was applied, while in PF14 and PF15 tests a spreader beam was used to redistribute the load between two webs, so to have the same eccentricity as in PF13. PF13 test resulted in a punching failure, while in PF14 and PF15 tests failure was governed by shear–torsion interaction. Compared to the single element capacity obtained in reference 13, the floor capacity in PF13 was 1.31 times higher, while an increase by a factor of 2.11 and 2.10 was observed in PF14 and 15, respectively.

A similar HC floor formed by 200 mm deep elements with an opening near the support was also investigated by Pajari,[34] see Figure 5b. Joints were cracked before test execution. Ten loading configurations were considered, and for each of them, the load was applied through a spreader beam on 4 webs, up to the service value. Subsequently, two tests were carried out up to failure, with the loads applied in positions 3 and 4 (Figure 5b). Compared to a single element test,[13] the failure load observed at position 4 was 19% higher. The measurements on the steel trimmer beam revealed that it carried about 20% of the failure load, whereas the remaining part was carried through the joints.

A HC floor subjected to long-term loading was studied by Zając et al.[35] Several loading schemes with uneven and even loading were applied, and displacements were recorded for each of them. For one chosen scheme, the load was left for 363 days, and deflection measurements were repeated during time. The final displacement of the floor increased by 180% compared to the short-term deflection. A smooth distribution of deflection in the slabs of the floor subjected to an uneven long-term load confirms the ability of the joints to provide redistribution.

Besides the experimental tests described above, several more tests on hollow core floors investigating other behavioral aspects can be found in the literature. A total of 20 tests investigating the behavior of HC floors on flexible supports were discussed in reference 38, while the behavior of hollow core floors in fire conditions was analyzed in references 39,40. The behavior of a 6 × 6 m HC floor with concrete topping subjected to long-term loading was studied experimentally by Ibrahim and Elliot.[41] Seismic performance of full scale HC floors was investigated in experiments by Corney et al.[42] and Büker et al.[43] However, in the abovementioned tests, HC floors were always subjected to a uniformly distributed load, did not include any opening and were characterized by a symmetric shape; therefore no load distribution phenomena could be observed.

2.2 | Relevant experimental investigations on single elements and two-slab assemblies

Apart from tests on floor assemblies, several experimental tests were carried out on two HC slab assemblies and on single units, which are relevant in the light of the studied phenomena. These tests investigated the role of longitudinal joints, the local effects induced by concentrated loads that can limit the floor capacity, or the system effects imposed by neighboring elements that can further impact the floor behavior. The most significant works available in the literature are briefly discussed below.

Capacity of longitudinal joints was investigated by den Uijl[44] on 800 mm long two HC slab assembly connected by a pre-cracked joint and tied at the ends with steel bars. Nine tests were performed on two types of 260 mm and one type of 400 mm deep units—see Figure 6. Despite the different shapes of the joints and the significant difference in the concrete strength between the units and the joint (which was respectively equal to 85 MPa and less than 20 MPa), none of the examined specimens collapsed due to joint failure. The observed failure always occurred due to the limited shear capacity of the top or bottom flange of the HC slab.

Shear capacity of longitudinal joints was investigated by Hong et al.[45] on the floor sub-assembly illustrated in Figure 7a. The tests were carried out referring to one setup without concrete topping, in which non-shrinking grout was applied for joint filling, as well as to three setups with a different concrete topping arrangement (30 mm thick, unreinforced; 50 mm thick, unreinforced; 50 mm thick, reinforced).

The absence of applied restraints, except for the one provided by the topping, could explain the failure mode detected at the end of the first test (without topping), which was characterized by the detachment of the joint from the adjacent slabs. In the case of the two assemblies with an unreinforced topping, a shear failure was observed, with cracks propagating throughout the interface between the precast and cast on site concrete. The failure load obtained for the assembly with 30 mm thick

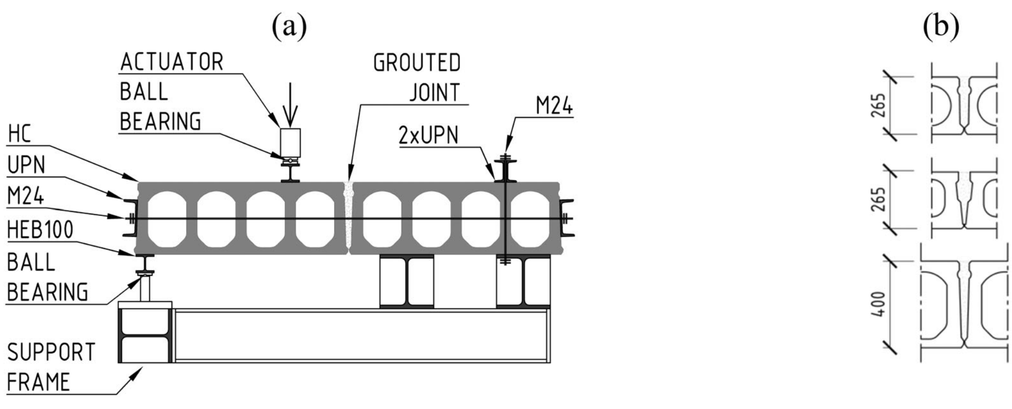

FIGURE 6 (a) Experimental setup of the tests performed by den Uijl.[44] (b) Geometry of the joints considered. *Source*: Adapted with permission.[44]

topping was close to the one obtained for the untopped specimen, while the specimen with 50 mm thick unreinforced topping failed at a twice bigger load. The specimen with 50 mm thick reinforced topping failed at a load that was further 10% higher, the failure was ductile and occurred due to topping separation from the HC surface.

Pisanty[46] studied the transverse bending behavior of HC slabs through experimental tests on 200-, 250- and 300-mm deep HC slab strips, having a length equal to their thickness, and subjected to 4 point bending, see Figure 7b. Two different configurations were considered, in which either the bottom or the upper flange was subjected to tension, respectively. It was observed that the capacity dropped with an increase in section depth, and that tensile stresses causing flexural failure in the bottom flange were within 75%–100% of the mean concrete tensile strength f_{ctm}, whereas stresses in the upper flange were within 60%–80% of f_{ctm}. These tests, although performed on strips of single elements, are relevant to the studied phenomena since they provide an insight into the transverse behavior of single units, which is important in floors subjected to concentrated loads. In these tests,[31–33] longitudinal cracks due to transverse flexure occurred before failure. By analyzing a slab strip simply supported on its edges, as shown on Figure 7b, a lower bound of transverse flexural capacity can be therefore obtained.

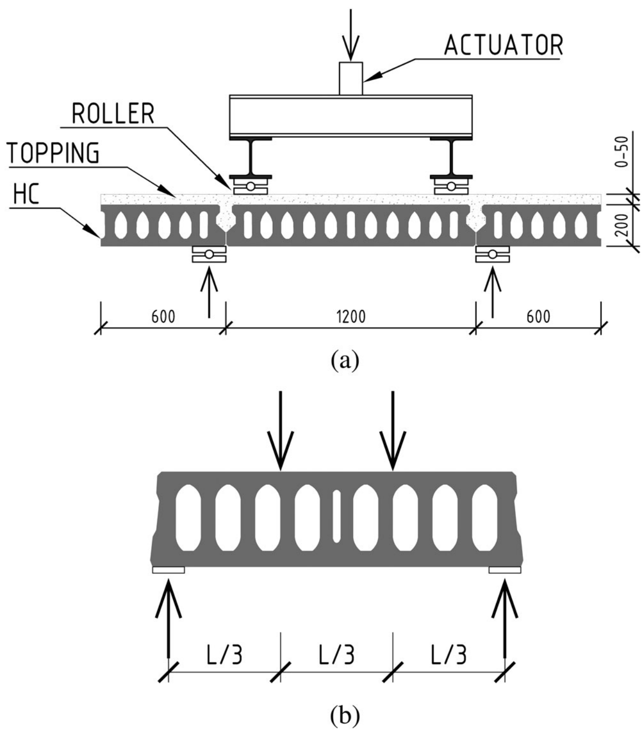

FIGURE 7 (a) Shear tests by Hong et al.[44]; (b) Four-point bending test setup by Pisanty.[46] HC cross sections should be intended as indicative. *Source*: Adapted with permission.[44,46]

Tests by Walraven et al.[47] concerned a 200 mm deep two-slab assembly subjected to a linear loading applied through two spreader beams, see Figure 8a. The obtained failure load in two slab assembly was 1.79 times higher than one obtained in a single slab test. Figure 8b reports the experimental load-strain curves plotted for both the slabs A and B. A ductile failure was observed, with strains distributed almost equally in both units, despite the fact that unit B was left unloaded.

Walraven[48] carried out three tests on two 265 mm deep slab assemblies, supported on 3 edges and subjected to 4 point loads applied in two different locations, see Figure 9. In the first two setups the assembly was supported on the shorter edges on neoprene pads, while in third setup neoprene was replaced by mortar. In all the setups steel plates were placed between HC and the support on the longer edge. The lowest failure load was obtained in the first setup, while the failure load in the second and third setups was 1.46 and 1.29 times higher, respectively. In the first test, cracks appeared near the corners and propagated till the joint, and finally the loaded slab failed in shear in the outer web. In the second test, corner cracks appeared in the unloaded element, while failure was preceded by the formation of a longitudinal crack in the loaded element parallel to the load location. No corner cracks appeared instead in third

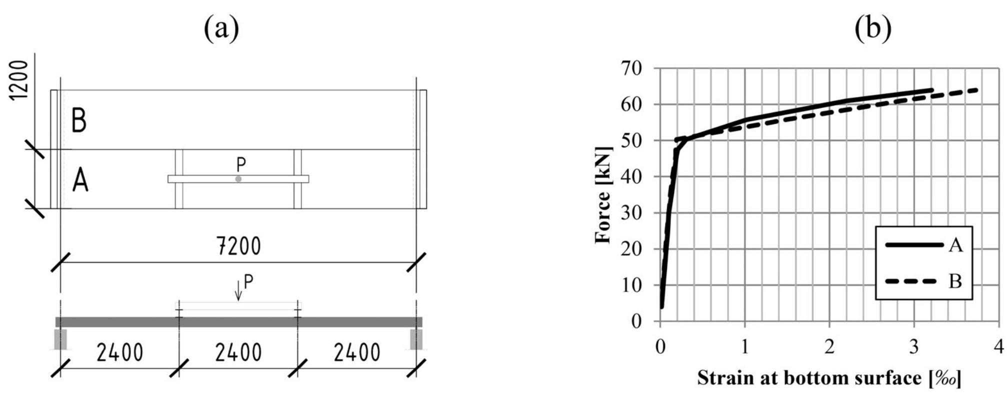

FIGURE 8 (a) Test setup of the experiments by Walraven, Huyghe and Stroband.[47] (b) Experimental load–strain curves measured at midspan under the load location.

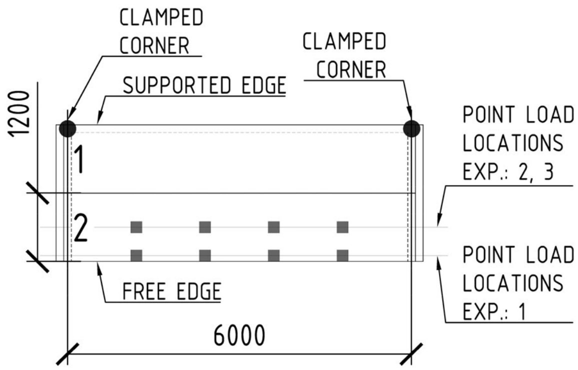

FIGURE 9 Test setup adopted by Walraven.[48]

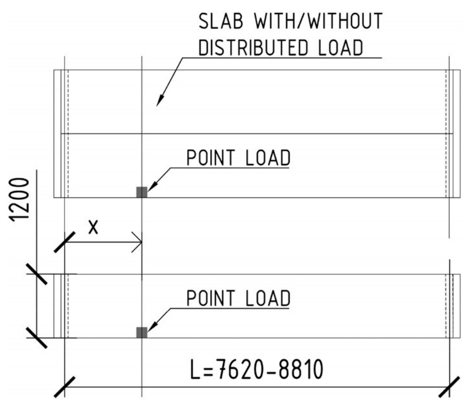

FIGURE 10 Experiments on concentrated load capacity by Aswad and Jacques,[49] two-unit assemblies (top) and single unit test (bottom).

experiment, but a similar longitudinal crack formed before the slab failure.

Aswad and Jacques[49] investigated the behavior of 200 mm deep single units, and several assemblies formed by two units subjected to a concentrated load applied over the outermost web at different positions along the span, see Figure 10.

The slabs loaded at one-third of the span ($x = L/3$), as well as those loaded at midspan ($x = L/2$) failed in punching, while specimens loaded closer to the support ($x = L/5 - L/4$) failed in combined shear and torsion. The failure mechanism of the two-slab assembly was identical to that detected in tests on single units. In one of the performed tests, the assembly formed by two slabs was subjected to a point load applied at midspan ($x = L/2$) of one slab, as well as to an additional distributed load equal to the service load in the adjacent one. In that case, the bearing capacity was 14% lower than that of a single slab without additional distributed load, whereas when the magnitude of imposed load was lowered the capacity of the two-slab assembly was almost identical to the capacity of the single slab. It can be thus concluded that, differently from the other previously discussed tests, a favorable effect of load distribution was not observed in this case.

Local failure of single HC slabs subjected to concentrated loading was studied by Lucio and Castilho.[50] Various loading positions were investigated across and along the slabs, and additional tests were also performed on specimens with filled cores directly under the applied load. Slabs loaded in their central part without filled cores first cracked longitudinally. After the appearance of longitudinal cracking, the lateral continuity of the slab was lost, and shear stresses in the web increased rapidly, leading to a shear failure of the loaded web at a loading level remarkably close to the cracking value. In the case of a unit loaded at its centerline, near the support and over one web, the failure load was even lower than the cracking load. Slabs loaded at the edge did not crack longitudinally but failed in a brittle way. Filled cores increased the ultimate punching capacity of about 30% in both loading scenarios.

Experiments by Thienpont et al.[51–53] concerned axially restrained single HC slabs subjected to four point bending. Two experiments were performed on axially restrained specimens, while one test was performed on an unrestrained element. Compared to the unrestrained specimen, the restrained units failed at a load 1.48–1.59 times higher. While the unrestrained element failed in a ductile way, a brittle failure was observed in restrained specimens. Although the tests were performed on single elements, they are considered relevant, since they indicate that the effects of the surrounding structure can largely affect the HC slab behavior. Such effect will be present in HC floors as well, and will largely depend on the support conditions, which in turn can affect the load distribution.

To summarize, the experimental studies carried so far confirm the ability of joints to redistribute vertical loads. However, the quantitative extent of this effect is highly variable, since tests were performed on specimens characterized by different cross sections, number of slabs, spans, load type and location, and also differed in terms of measured physical quantities. Some of the abovementioned experimental programs provide a comparison with the behavior of a single element, so giving a direct measure of redistribution effects, whereas some others do not. Therefore, a simple comparison among the tests is often not possible, and a reliable quantification of the redistribution effects cannot be done. It should also be noted that the amount of experimental data is very limited and it is the corresponding documentation available in the literature is limited as well. This makes extremely difficult to use these data for building new computational models, both analytical and numerical. The review of the literature has also shown that some studies[49] do not confirm the possibility of distribution – therefore an important research question raises about the way and possibility of formulating reliable consideration on load distribution in HC floors, especially for those subjected to complex loading or supporting conditions.

3 | CURRENT ANALYTICAL APPROACHES

The issue of vertical load distribution has been deeply studied analytically in bridge structures by, among others, Guyon, Massonnet and Bares.[54] They assumed that an orthogonal system of beams could be transformed into an equivalent continuous orthotropic plate. It should be however noted that the orthotropic plate method should be used for systems formed at least by five beams, although the exact minimum number of beams is cumbersome to define. A similar approach could be also used for HC slabs, which—differently from beam grids—are linearly connected to each other though cast-on-site joints. Assuming that, an orthotropic plate model can be used, by posing that the transverse stiffness is equal to zero. Such an approach is also suitable for the analysis of bridges formed by precast beams connected by hinges, according to Cusens and Pama.[55] Spinelli[56] proposed a discrete method based on the equivalent orthotropic plate approach, in which the floor is treated as a system of parallel Saint Venant beams linearly connected through hinges, and behaving linearly elastic. This discrete model has been revised and further developed for HC floors by Bernardi et al.,[57] according to the basic assumptions shortly recalled below.

Given that the slabs are interconnected longitudinally by cylindrical hinges that transfer shear forces only, the compatibility condition between the deflections of the adjacent plates should be satisfied in correspondence of longitudinal joints, according to Figure 11 and Equation (1):

$$v_j(x)+\frac{b}{2}\varphi_j(x)=v_{j+1}(x)-\frac{b}{2}\varphi_{j+1}(x), \tag{1}$$

where b is the width, and $v_j(x)$ and $\varphi_j(x)$ are the deflection and rotation functions of the jth beam, respectively. Equation (1) was derived under the simplified assumptions that all the slabs in the floor have the same geometry and the same material properties, and that the rotation angles are small enough so that $tan(\varphi)\sim\varphi$. Considering that each unit behaves as Saint Venant beam, Equation (1) can be rewritten in the following form:

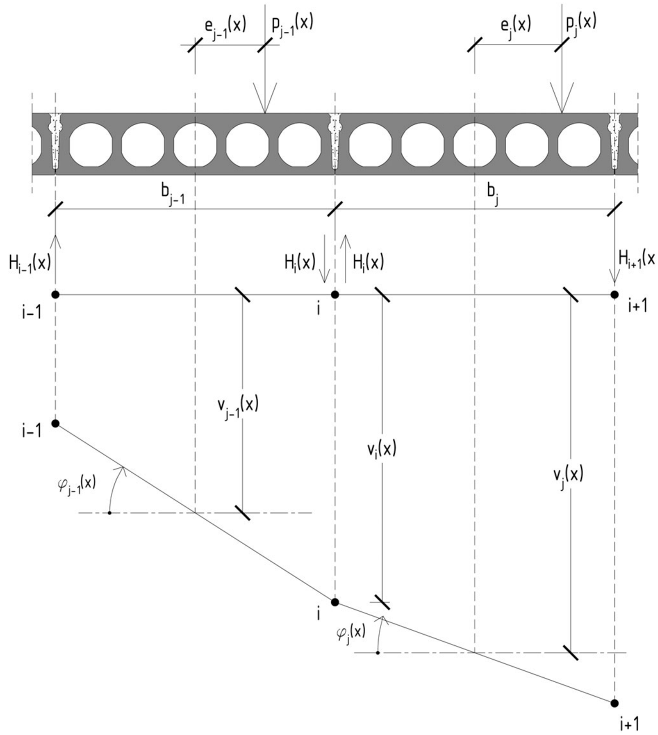

FIGURE 11 Illustration of the equilibrium condition in a longitudinal joint.

$$\frac{q_j(x)}{EI}+\frac{m_{tj}^{II}(x)}{GI_t}\frac{b}{2}=\frac{q_{j+1}(x)}{EI}-\frac{m_{tj+1}^{II}(x)}{GI_t}\frac{b}{2}, \tag{2}$$

where EI is the flexural stiffness and GI_t the torsional stiffness of an individual unit, respectively, while $q_j(x)$ is the equivalent transverse load, and $m_{ti}(x)$ the distributed applied torque. Since these latter quantities can be expressed as a function of the external load $p_j(x)$ and of the shear forces $H_i(x)$ and $H_{i+1}(x)$ transmitted along the adjacent joints, in reference 57, Equation (2) was further rewritten so that the only unknowns were the shear forces in each individual joint. Having solved the system, the shear forces and the internal forces in each individual unit could be obtained under a general loading configuration, taking into account the vertical load redistribution in the floor.

The issue of vertical load distribution in HC floors is sparsely mentioned in codes and regulations. Due to practical reasons, it is common to use simplified graphical methods as a mean to include vertical load distribution in floor design. One of such methods can be found in the informative annex of the European Standard EN 1168.[4] The method assumes the elements as isotropic or anisotropic linear elastic plates, with longitudinal joints behaving as hinges transferring shear forces only. Redistribution factors are provided for point and line loads located on the edge and on the center of a floor formed by 5 slabs, for different floor spans. The so obtained values can be also used at ultimate limit state by multiplying the coefficient referred to the directly loaded element for a fixed value of 1.25, while the loading amount carried by adjacent elements may be decreased by the same amount according to the ratio of their loading percentages. If topping is used, no correction factors are used at ultimate limit state. Apart from simply supported floors, a series of graphs for floors supported on 3 or 4 edges are given, which also provide support reactions on the support parallel to the floor span.

Theoretical background of EN 1168 provisions can be found in reference 58 and in the FIP document.[59] The latter gives a good insight in the approach followed to derive load distribution graphs for line loads. The FIP method shares the same assumptions as discrete models, it mentions however that the obtained load distribution factors shall be applied to bending effects only, whereas code provisions[4] do not specify such limitation. The distribution factors are given as a function of floor span, loading position, and loading type, disregarding the influence of HC cross-section geometry. However, the ratio between flexural and torsional stiffness is generally required for load distribution analysis in both continuum[54] and discrete models.[57,60] The report[59] suggests that the graphs in EN 1168 have been prepared for a constant ratio that was usual for hollow core cross sections with circular voids used in 1980s, and a depth limit of 320 mm was mentioned as well; however such limitations are not mentioned in EN 1168.[4] These limitations were also highlighted in a work by Lindstrom,[61] who adopted a method similar to reference 57 to derive a series of graphs providing load distribution factors, such those reported in EN 1168.[4] However, in this case, different factors were given for support reactions and bending moments, and each graph was prepared for two flexural to torsional stiffness ratios, respectively equal to 0.60 and 1.20. According to Lindstrom (49) a linear interpolation could be used for different ratios, and therefore the method could be extended to various HC cross sections.

The limitations of the approach adopted in the Standards were also highlighted by Parkinnen, who studied the load distribution in 400 mm deep HC slabs.[62] He compared the analytical provisions of the FIP document[59] with the results of his experimental program on a 400 mm deep and 6 m long HC floor,[32] and he also performed finite strip numerical analyses. Parkinnen concluded that the distribution of bending moments and shear forces due to point loading given in FIP recommendations diverged greatly from test results. The scatter between the experimental and analytical results was especially visible in terms of support reactions, which were significantly underestimated by the FIP graphs. Moreover, a different floor behavior was observed at serviceability and ultimate limit state conditions, especially under shear. As a result, a proposal of load distribution graphs for 400 mm deep units was drafted. The graphs differed significantly from the FIP recommendations, but did not cover the case of loading applied on floor edges. Support distribution graphs did not include more than 3 elements, thus possibly suggesting that only 3 slabs cooperate when reaction distribution is considered.

Recommendations on the load distribution can also be found in the PCI Manual for the Design of Hollow Core Slabs and Walls.[63] Differently from the European provisions, which account for the phenomenon through load distribution factors, the Manual refers to the concept of load distribution width. The latter is defined as the effective resisting section for any type of load to be distributed between HC slabs. Internal forces in the slabs are obtained by dividing the moment or shear forces caused by a point or linear load in a single element by the calculated distribution width. Figure 12 presents the distribution widths for loads in the center and on the edge of the floor as a function of its span (L).

As it can be seen, in support regions the load should not be redistributed, and should be further increased in case of loads placed on the edge of the floor. The manual explains that such measure takes also into account the effect of shear stresses due to torsion. By using this simplification, the method can be applied for the prediction of peak values of moment and shear forces, thus suggesting that in such case no further check is required for torsion, if the slab is able to withstand a significantly higher shear force. This approach is quite different from that adopted in the European standard,[4] which requires shear–torsion interaction to be checked using a simplified linear dependency between shear force and torsional moment.

The concept of distribution widths was further expanded by Stanton,[64] who proposed different analytical equations to evaluate the redistribution effects in terms of bending, shear, torsion and deflections, due to the presence of concentrated loads acting on the floor. It is worth noting that the distribution widths calculated following this approach provide results different from PCI Manual,[63] which provides a single distribution width. The widths for shear and bending are expressed as a function of the distance between the applied load and the considered section, while distribution width for torsion depends on the geometrical properties of slabs, namely their total width and the width of the webs.

Although the above-mentioned provisions share similar assumptions, the results provided can differ significantly. To clearly show some of the differences to the reader, load distribution in flexure and shear obtained

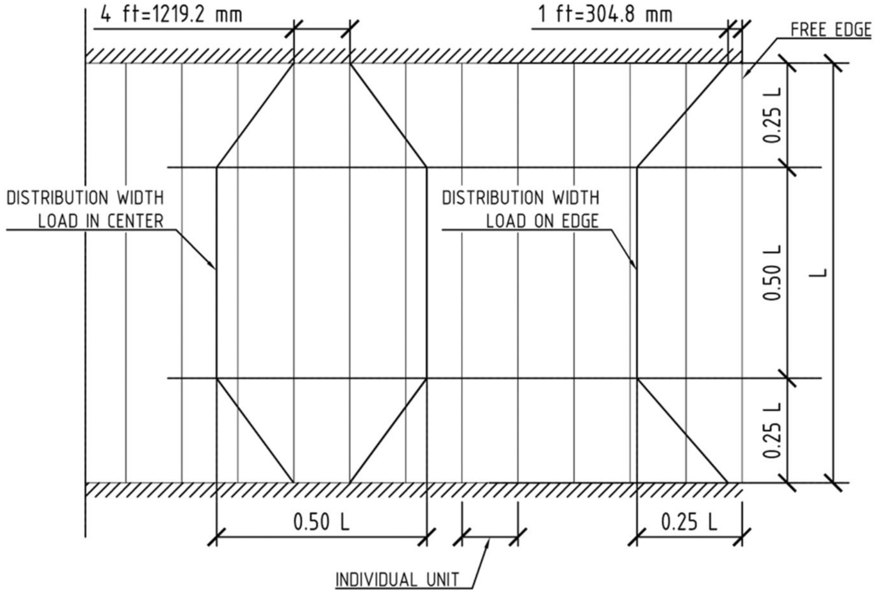

FIGURE 12 Load distribution widths according to reference 63.

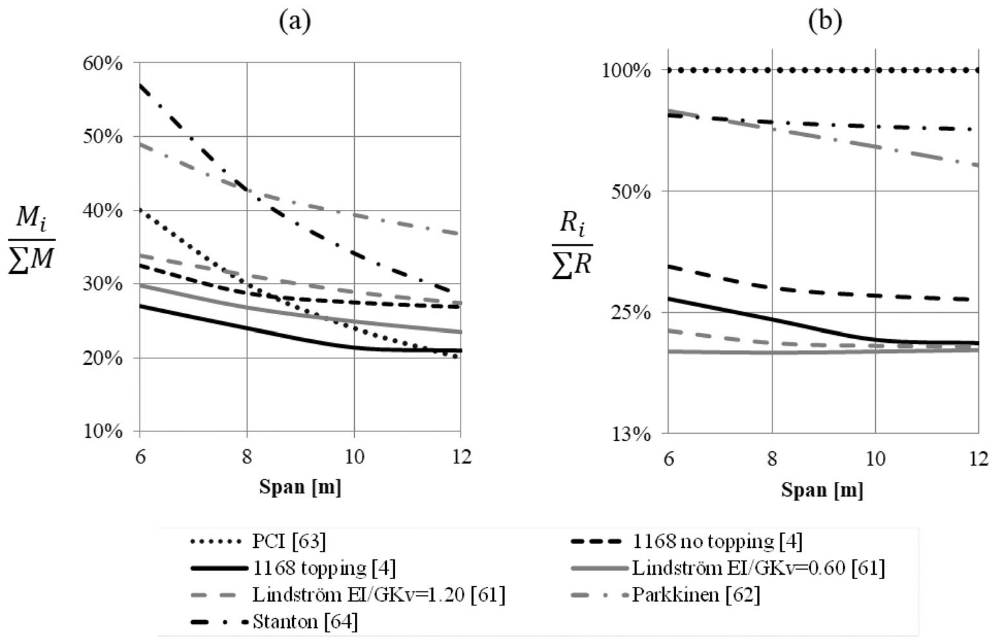

FIGURE 13 Comparison of redistribution effects obtained from various provisions. (a) Peak bending moment distribution and (b) Support reaction in a directly loaded element subjected to a point load in the center of a floor in its midspan. As published in reference 37.

from different provisions for a directly loaded element subjected to a point load in a midspan, is compared in Figure 13. More details about the methodology used to derive the curves presented below, as well as the results referred to other load type and position can be found in reference 37.

Load distribution in HC floors with wide cast on site reinforced concrete joints was studied by Song et al.[65] Based on the results of an elastic finite element analysis, an analytical method was proposed, which describes the floor deflection in the longitudinal and transverse direction through cubic and quadratic polynomial functions, respectively. Load distribution in bending is determined on the basis of the sum of the transverse deflection in each element compared to the transverse deflection of the whole floor.

All the above-mentioned analytical approaches commonly assume longitudinal joints to behave as cylindrical hinges that transfer shear forces only. Such assumption stems from crack occurrence at the weak interface between the precast slab and cast on site joint. These cracks are induced by differential shrinkage strains, temperature effects and restraints imposed to the floor by adjacent structural elements.[3,66,67] Despite that, the joints are able to transmit shear forces due to the shear friction mechanism and the interlocking of shear keys formed by the grooves at the side of the slabs. Broo[68] mentions however that the joints are able to partially transfer also the transverse bending moments in untopped floors through compressive contact forces that occur due to adjacent slabs rotation.

Additional topping layer undoubtedly affects the load distribution, possibly allowing the joints to transfer transverse bending moments, and thus further improving the floor capacity.[45] The presence of well-connected topping increases flexural stiffness and resistance,[69] for sufficiently thick topping layer the deformability in the elastic stage becomes closer to that of a solid section. The influence of the topping layer on HC floor behavior was studied experimentally and numerically mainly on single elements,[17,19,70–74] while topped floors were studied numerically in references 5,6. Nevertheless, apart from a simple guidance in EN 1168,[4] no analytical models or provisions exist for topped HC floors in context of load distribution.

4 | DISCUSSION AND CONCLUSIONS RELATED TO CALCULATION METHODS

As it can be seen from Equation (2), the response of a HC floor depends on its flexural and torsional stiffness, which in turn are affected by cracking. Individual HC units can be subjected to a combination of flexure, shear and torsion, and each of these responses affect the flexural and torsional stiffness differently. While the effect of normal cracks on flexural stiffness can be easily derived, the effect of normal cracks on torsional stiffness has not been studied broadly, especially in case of elements without shear reinforcement. This problem, narrowed down to HC slabs, was studied by Azizov et al.,[75,76] but the approach discussed in reference 76 still requires additional numerical analyses to derive the post-cracking torsional stiffness.

As shown in the discussed experimental tests,[31–33,50] longitudinal cracks can form even before than normal cracks, but their presence is not strictly correlated to the failure condition, since transverse stresses can still be transferred throughout the cracks. The background documents of EN 1168 method[58,59] suggest that at the ULS an element affected by longitudinal cracking should be split into two parts at the longitudinal crack location, and therefore the same principles illustrated in Figure 11 should then be applied to a system that contains an additional interconnected element.

EN 1168[4] does not discuss much the problem of load distribution at ULS, but simply suggests to slightly alter the load distribution factors derived from elastic analysis. Some limitations are however given for the values of point and linear loadings, due to local effects such as punching, transverse bending and joint capacity. In more detail, point or linear loads should be limited to a longitudinal cracking value that depends on the unit span, width, and section modulus, as well as on the tensile strength of concrete. However, such an approach can underestimate the cracking value observed in experimental tests.[36,50] EN 1168 also limits the maximum value of applied point loads so to avoid punching. However, experimental tests[50] on single HC slabs indicate that this limitation might not be correct. Furthermore, analysis of experimental tests on HC floors[31,32] performed in reference 36 indicate that in case of floors the actual punching capacity could be significantly higher. A similar conclusion was also made with regards to the capacity of longitudinal joints.

For shear and torsion, EN 1168 provides a linear interaction, by assuming that capacity is governed by failure in the web, where combined shear and torsion stresses accumulate. Gabrielsson[77] and later Broo[68] concluded that the interaction of shear and torsion is not linear, and that the EN 1168 provisions provide conservative results compared to numerical analyses and experimental evidences. In the case of pure torsion, the method overpredicts the capacity since the response is governed by the capacity of the upper or lower flange. Numerical analyses performed by Broo also proved that the presence of adjacent elements positively affects the ultimate shear–torsion capacity of the directly loaded element.

The issue of shear, torsion and bending interaction in HC floors was not broadly covered in analytical, numerical, or experimental studies. Some studies on this interaction exist, but mainly concern non prestressed[78] and shear reinforced elements.[79–81] The only research related to HC slabs that sparsely mentioned this interaction is the one by Gabrielsson,[77] who proposed a modified analytical model for a section without transversal reinforcement based on reference 82, and compared the results with two experimental tests on single units.

Finally, no provisions can be found in EN1168 regarding the presence of openings in HC floors, while some simplified provisions based on the distribution width are provided in PCI Manual.[63] The impact of the openings on floor capacity was extensively studied numerically at the University of Parma.[5,6,8,83] The numerical analyses were validated against experimental tests on single elements and floors.[31,33,34] Based on a parametric finite element analysis, an analytical method was then proposed,[84] which allows predicting the effects of large openings on the serviceability and ultimate capacity of HC floors.

5 | FINAL REMARKS

In this paper, load distribution in HC floors is examined, through a critical and systematic review of analytical relationships/models, code provisions, experimental data and testing procedures. Based on this literature review, the following aspects can be evidenced:

1. Existing experimental and analytical approaches clearly indicates that HC floors are able to effectively cooperate when subjected to concentrated vertical loads or when interested by the presence of openings. The behavior of these floors depends on the type (point/line load) and position of the applied load, the geometrical properties of individual units, the floor span, the considered load effect (e.g., shear, bending, torsion, and deflection), as well as on the location and size of possible openings.
2. In analytical approaches it is commonly agreed that longitudinal joints behave as cylindrical hinges that transmit shear forces only. This assumption is justified by the presence of cracks caused by shrinkage, temperature and restraints imposed by adjacent structural elements.[3,66,67]
3. Despite the similarities in the formulation of the analytical models, the obtained results can significantly differ when compared to each other, or when they are compared to experimental results.[37,62] It is important to underline that current design provisions[4,63] take into account only a limited amount of parameters, and therefore might not always provide fully reliable results, especially in predicting shear redistribution among the slabs. In order to clarify this aspect, the reaction force redistribution obtained from experimental test[31] is compared to the analytical values on Figure 14. The graphs present the redistribution of the reaction force as a percentage of the total undistributed reaction in the directly loaded element. The latter shall be intended as the total reaction force at the support obtained from a simply supported element analysis. Reaction exceeding 100%, resulting from Stanton's approach[64] as shown on Figure 14a, stems from a simplified approach to the torsional effects, similar to one in PCI Manual.[63] In this approach, torsional effects are taken into account by means of amplifying the shear force, therefore in a particular case of load on the edge the overall reaction can exceed 100%.
4. Available analytical models are based on linear elastic behavior. Since load distribution can also be used in ULS, such an approach might not be exhaustively accurate. However, experimental data suggests that HC floor can withstand loads much higher than single HC slabs.
5. Experimental failure loads obtained for HC floors subjected to line loads[28,47] significantly exceed the corresponding values obtained from tests on single elements. The failure mode in case of a floor can be brittle compared to the ductile failure of single element[28]; however, in two slab assembly,[47] failure mode remained ductile, and therefore a possible effect related to the number of slabs forming the floor could be highlighted. It is stated that the FIP report,[59] which represents the basis for the draft of European provisions,[4] can predict the failure load due to linear loads effectively, based on the comparisons with experimental results obtained by Lejeune and Niet.[28] This conclusion was, however, based on just a single experimental test, and experimental programs describing the behavior of HC floors subjected to line loads in terms of both deflections and support reactions are still missing in the literature.
6. Experimental studies on floors subjected to point loading[31–34] evidence an enhancement in terms of bearing capacity with respect to the case of a single unit. These studies, together with experimental tests on single elements,[49,50] show that HC floors subjected to concentrated loads can be prone to punching failure. Such an occurrence is not surprising, since a similar condition usually apply to solid homogeneous floors. However, it was observed in reference 36 that the presence of adjacent elements can positively affect the punching capacity. That phenomenon seems to be on the contrary underestimated by EN 1168.[4] The positive effect of load redistribution on the bearing capacity of HC slabs subjected to point loading was also confirmed by numerical analyses concerning shear–torsion interaction.[68]
7. Load distribution effects were observed in experimental tests on HC floors with openings.[26,27,30,34] Indeed, the tested floors either did not crack or fail despite the heavy loads applied,[26] or failed at a load that exceeded the predicted value,[27,30] or the one obtained from a single element test.[34] In references 30,34, it was concluded that the main part of the load is spread through the longitudinal joints also in case of openings sustained by steel or concrete trimmer beams, thus additionally proving the ability of longitudinal joints to effectively ensure the load transfer.[34,44] The positive impact of adjacent elements on the performance of floors with openings was also confirmed by broad numerical studies discussed in references 5,6,8,85 that resulted in the proposal of a simplified analytical method,[84] which is the only available in the literature apart from simplified provisions given in the PCI manual.[63]
8. In the case of linear and point loads applied eccentrically, as well as in the case of floors with openings, a complex stress state due to shear–torsion and

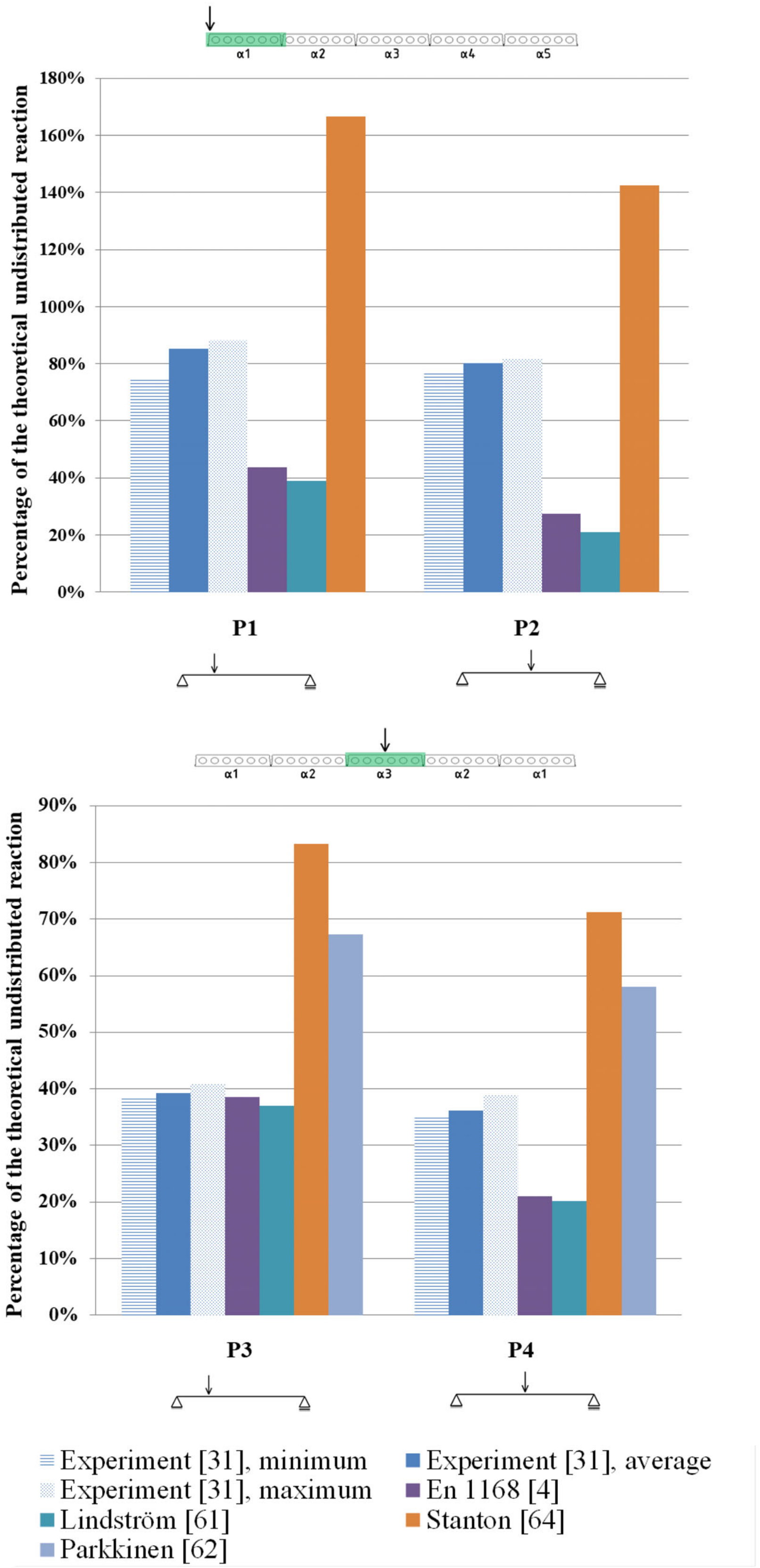

FIGURE 14 Redistribution of reaction forces as experimentally measured on a full scale HC floor[31] compared to analytical results provided by references 4,61–64. (a) Point loads on the free edge of the floor; (b) Point loads on the central element. First published in reference 37.

bending-normal forces actions should be considered. While specific attention was paid to the zones where bending moment is negligible,[9,10,13,33,34,68] the combined effects of shear, bending and torsion were so far not broadly investigated either in experimental tests, nor in analytical models and numerical studies.

9. Apart from some simplified rules suggested in EN 1168,[4] the effect of concrete topping on load distribution and bearing capacity of HC floors is not taken into account in any of the above-mentioned analytical models or provisions. A positive impact of topping layers on the behavior of joints was proven in experiments by Hong et al.[45]; however, no tests were carried out on HC floors with toppings.
10. While much attention has been paid to the capacity of evenly loaded HC floors on flexible supports[38,86] to the behavior of floors during fire,[39,40] the issue of load distribution was not investigated in such conditions. Load distribution in continuous floors was neither investigated.
11. Research on the compressive and tensile membrane action in HC slabs[51–53] indicate that the restraint imposed by the structural system can impact the floor behavior, however, no analytical models exist that would allow taking that effect into account.
12. Although a significant amount of experimental programs have been carried out on individual HC elements over the years, the number of test on whole HC floors investigating load distribution is much more limited. Moreover, only few of them[31–34] have been carried out up to failure, and can be therefore proficiently used for the validation of numerical and analytical models.

6 | FUTURE PERSPECTIVES

Simply supported, evenly loaded HC floors, with regular geometries are rarely used in practical applications and therefore the knowledge of the spatial behavior of the floor and of the loading redistribution that takes place among panels is of paramount importance, leading to significant benefits in terms of general costs and sustainability.

Due to the uncertainties surrounding the load distribution phenomenon, as well as the lack of well documented experimental data, this aspect is rarely considered in design, or in some cases, especially concerning shear, is doubtful how it should be properly taken into account. Future research in this field shall concentrate in providing a reliable, comprehensive, and well-understood analytical model to be used for the determination of internal forces in HC units forming the floor. In the authors' opinion, such model should also clearly state its limitations, since it would not be possible to draft general rules covering every possible design situation, due to the high number of involved parameters and the variety of HC applications. For all the practical cases not directly covered by such analytical approach, FE analyses should be required. For this reason, authors believe that further research should also concentrate on the elaboration of recommendations for proper and efficient finite element modeling of HC floors. Thanks to the versatility of numerical methods and considering the popularity of finite element analyses in day-to-day design, such an approach could certainly provide general results for HC floor calculations. Nevertheless, due to the issues and complications still surrounding nonlinear analyses of concrete structures, analytical provisions on the capacity of HC slabs should necessarily be further expanded, too. Regarding some specific aspects of HC floors behavior that have been little investigated so far and that deserve further attention in near future, it should be certainly mentioned the interaction of shear, bending, torsion and normal force action, as well as punching failure. Since cast in place concrete topping undoubtedly improve structural performance of HC floors at serviceability and ultimate limit states, further provisions regarding its presence, the presence of reinforcement and the surface roughness should be provided. Since HC floors are rarely simply supported in design practice, effects imposed by support conditions and surrounding structure should be further investigated.

It is also desirable to expand the existing experimental dataset, so that analytical and numerical analyses could be further validated. To avoid misinterpretation of the experimental data, strains in both longitudinal and transverse directions of the floor should be measured, together with deflections and reaction forces.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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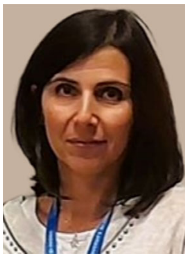

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