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Influence of Load Pattern on the Shear Strength of Hollow Core Slabs in Uncracked Sections

Marco Breccolotti[1], Marco Pecetti[2], Costanza Vittoria Fiorini[3]
[1]Department of Civil and Environmental Engineering, University of Perugia
via G. Duranti 93, Perugia, Italy, marco.breccolotti@unipg.it
[2]Generale Prefabbricati S.p.A.,
Centro Direzionale Quattrotorri, Ellera Scalo, Perugia, Italy, m.pecetti@generaleprefabbricatispa.com
[3]Department of Astronautical, Electrical and Energy Engineering, "Sapienza" University of Rome
Via Eudossiana 18, 00184, Rome, Italy, costanzavittoria.fiorini@uniroma1.it

Abstract – Precast hollow core slabs are frequently used to cover large spans for industrial, commercial and residential buildings. Their use has been proved during many years of application to be reliable and economical. However, their construction methods, whether they are extruded or slip-formed, do not make it possible to insert shear resistant reinforcements. For this reason, there are still today significant inconsistencies between experimental data of shear strength of these elements and design strength provided for by the specific structural standards, especially for slabs of greater thickness. In this work, additional considerations, with respect to those already present in the literature, are made on the influence of applied load type (concentrated or distributed) and on the distribution modalities of the stresses upon collapse between the different webs. Detailed numerical analyses are carried out with the commercial FE code Abaqus to determine the shear strength in the uncracked bending zones and to individuate the crack pattern at collapse. The first results of the investigations indicate that the shear strengths of hollow core slabs for distributed loads are always greater (between 22.9% and 41.1% for the investigated slabs) than those observed for concentrated loads.

Keywords**:** Hollow core slab, Shear strength, Load pattern, Numerical modelling, Crack pattern.

1. Introduction

Precast hollow core (HC) slabs, together with other precast and prestressed elements [1], represent a fast, economic and reliable solution for realizing floors and roofs in industrial, commercial and residential buildings. The large assortment of thicknesses and prestressing reinforcements makes it possible to use these structural elements for loads up to 33 kN/m^2 with spans in the range 4 - 20 m [2].

Compared to other reinforced or prestressed concrete elements, HC slabs are produced with specific techniques and without shear reinforcements. For these reasons, structural codes provide specific design rules [3-6].

While bending moment design equations generally find good correspondence with experimental data, greater uncertainties are found in the shear verification formulas. This occurs in both cracked and non-cracked zones from bending-moment with the latter being more critical due to the high shear stress present at the supports.

For instance, Brunesi and Nascimbene [7] numerically assessed the shear strength of precast prestressed hollow core slabs for 200, 265, 320, 370, 400 and 500 mm thick units with circular and non-circular voids. The comparison between experimental results and analytical estimates obtained by common design Codes (EC2, EN 1168, ACI and CSA), allowed to quantify the inaccuracy of design Codes equations especially for deep slab sections with flat webs where the shear stress peak is localized below the centroidal axis. Based on the results of numerical simulations, the authors proposed a closed-form expression to be used as a preliminary-design-stage tool for analytical web shear strength assessment of HC slabs.

Similar conclusion were also reached by Tawadrous and Morcous [8] some years later. The authors compared ten different shear strength provisions adopted by ACI 318-14 [9], AASHTO LRFD 2014 [10], CSA A23.3-04 [11], JSCE 2007 [12], fib MC 2010 [13], AS 3600-2009 [14], EN 1168 [3], and Yang's method [15] using a database of 51 web shear tests of deep HC slabs. The obtained results indicated that the different shear strength provisions vary significantly with respect to each other and, therefore, different modification factors need to be used.

The lack of a consolidated state of the art on the topic of shear strength of HC slabs is evidenced by changes made on this issue in the recently enacted structural codes. Park et al. [16] compared the revised ACI318-08 Building Code Requirements with the previous ACI318-05. According to the more recent standard, the web-shear capacity of thick hollow-core member over 315 mm depth without the minimum shear reinforcement should be reduced in half. Based on new shear tests on HC members and on shear test data collected from previous studies, observing that the new standard may result in an excessively conservative shear while the previous one provided unconservative results not only for the thick PHCS members ($h > 315$ mm) but also the thin PHCS members ($h < 315$ mm), the authors introduced a simple method to estimate the HC slab shear strength that provides a sufficient margin of safety and economical structural design of PHCS members.

Nguyen et al [17] conducted shear tests on four precast, prestressed concrete hollow core slabs with depths ranging from 320 to 500 mm observing two distinct modes of failure, i.e., web-shear and flexural-shear. Shear strength results of the specimens obtained from the experimental program were compared to those predicted by EN 1168 and ACI 318-14. The comparisons showed that in some instances, these codes overpredict shear capacity of the tested specimens. Parametric studies showed that concrete strength plays a dominant role in the web-shear performance while the choice of angular or smoother-surface void shapes does not lead to a noticeable difference in web-shear capacity. The authors further observed that web-shear strength of PCHC slabs decreases with increasing prestressing force. A similar observation was made by Lee et al. [18]. The researcher noticed through comparison with past studies, that the web-shear strength of HC slabs is influenced by compressive stress due to prestress at the centroid, compressive strength of concrete, and shear span-to-depth ratio.

A relevant difference between the code predicted shear strength (EN 1168) and the experimental test results for 500 mm thick slabs was also observed by Michelini et al. [19]. The authors also carried out non-linear 2D finite element model to predict the stress distribution and crack pattern within the slabs, obtaining a good match with experimental results.

Finally, Sarkis et al. [20] observed that the shear strength is a function of the point of application of the concentrated load. The researchers investigated three values of the ratio between shear span and unit depth (1.5, 2.5 and 3.5) finding a minimum value of the shear strength for the aspect ratio value of 2.5.

In this work the attention is focused on the effect that different types of load (uniformly distributed or concentrated in different positions) plays on the shear strength of HC slabs in the zones not cracked by bending moment.

2. Programme of the Investigation

In order to investigate the influence of load type and position, numerical models of 3 slabs with thickness 260, 320 and 400 mm have been developed with the commercial FE code Abaqus. Information on the detailed FE models are reported in Sec. 4. The cross sections of the investigated slabs and their main dimensions are shown in Fig. 1.

A total number of 15 simulations have been conducted for each slab. In the first simulation a distributed load is applied to the complete upper surface of the slab. This simulation is representative of real load condition. Other simulations apply a distributed load in one or two surfaces (100 mm wide) placed only at the initial side of the slab or at both, initial and final, sides. Being the surface very narrow, the load type is considered as concentrated. These simulations are representative of load tests generally realized on HC slabs. The complete description of the numerical simulation is resumed in Tab. 1 where the distances are between the borders of the slabs and the loaded surfaces.

Table 1: Load position and type for different simulations (L= slab length, in= initial, fin= final, dist= distributed, conc= concentrated).

simulation n.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
load pos. (mm)	0-L	250-350		350-450		450-550		550-650		650-750		750-850		850-950	
side	---	in	in+fin	in	in+fin	in	in+fin	in	in+fin	in	in+fin	in	in+fin	in	in+fin
load type	dist	conc	conc	conc	conc	conc	conc	conc	conc	conc	conc	conc	conc	conc	conc

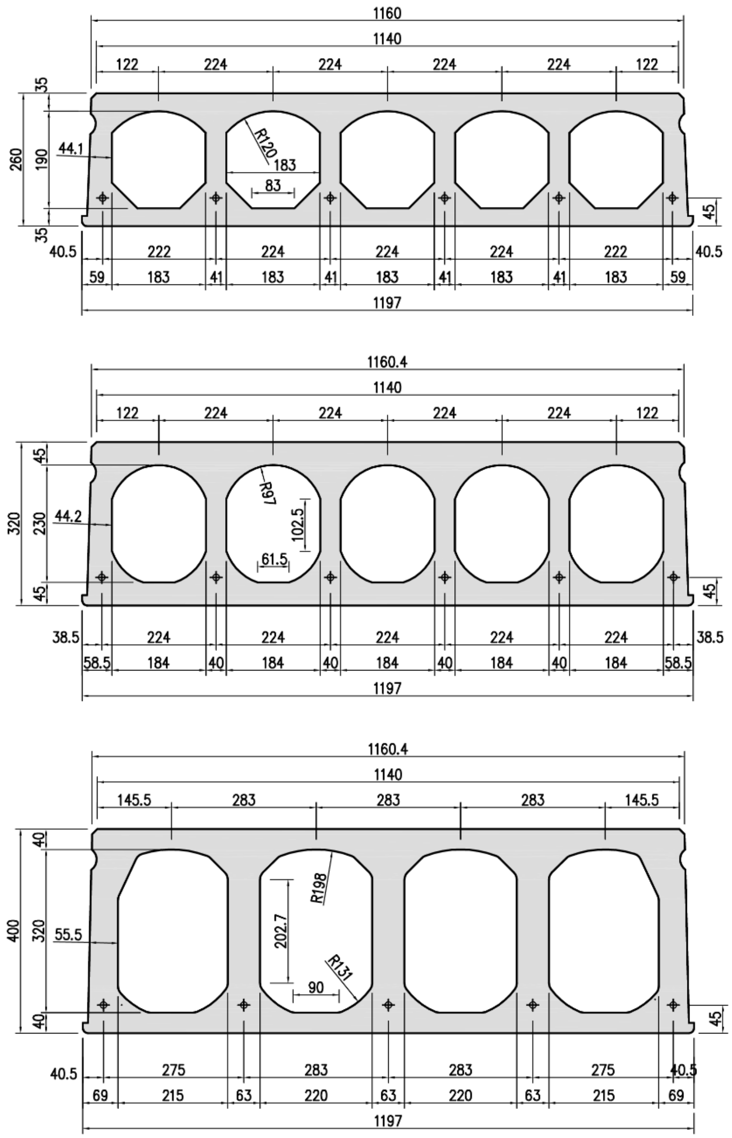

Fig. 1: Geometrical properties of the investigated HC slabs.

3. Numerical investigations

The numerical investigations have been carried out with the commercial FE code Abaqus, successfully used by the authors in other investigations [21-22].

3.1. FE models

Concrete parts and rubber pads at bearings have been modelled with 8-node linear bricks (C3D8R elements) while 2-node linear 3-D trusses (T3D2) have been used to model prestressing strands. These latter have been embedded in the concrete without relative slips between the two materials. Prestressing forces have been applied defining suitable thermal properties and temperature variations in the prestressing strands. The three-dimensional views of the FE models are shown in Fig. 2.

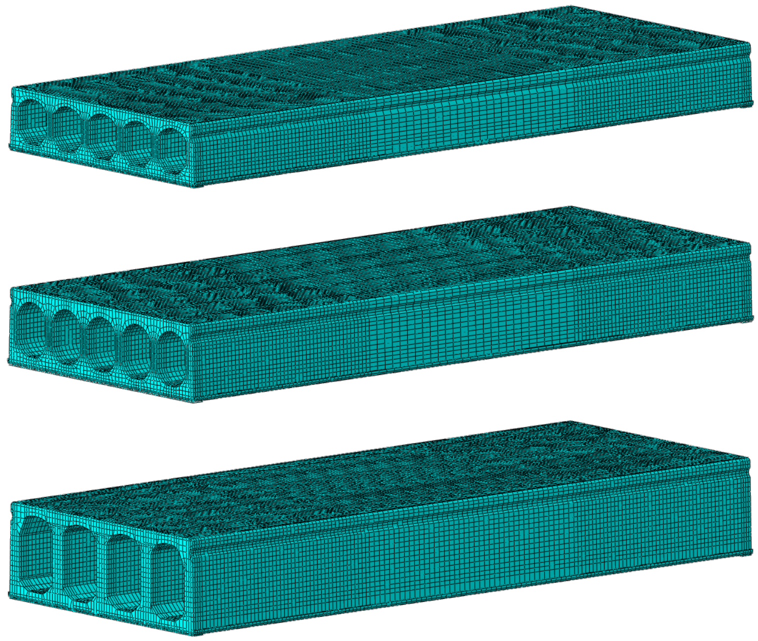

Fig. 2: 3D models of the investigated HC slabs with different thickness: top 260 mm, centre 320 mm, bottom 400 mm.

Prestressing transfer at slab ends were introduced in the numerical simulations by suitable reductions of temperature variations. Elasto-plastic behaviour with strain hardening has been used for the prestressing steel while the concrete behaviour has been modelled with the Concrete Damaged Plasticity behaviour available in Abaqus. To better define the numerical values of the parameters involved in the CDP algorithm, reference has been made also to indications found in the available literature [17,23-24]. In particular, a value of 0.0002 has been assumed for the viscosity parameter.

A vertical pressure is applied incrementally to the surfaces listed in Tab. 1 for each slab. It is assumed that the collapse occurs when the calculation does not reach converge and the simulation is terminated.

3.2. Results

With the pressure applied at the time instant the simulation is terminated, the vertical reaction at the initial support is calculated. The results of every simulation for the three slabs are shown in Fig. 3 where the shear strength is plotted against the distance d of the resultant of the applied pressure from the slab end. It can be noted that the shear resistance has a maximum in correspondence with the minimum distance between the support and the resultant of the applied forces for every slab. Moving away, the shear resistance decreases until it reaches minimum values for distances in the range 600 – 900 mm for the different slabs. Some differences between the results of the simulations for one (dotted red lines) or two (dash-dot blue lines) concentrated loads can be noticed in the graphs, especially for the one with greater thickness.

The same data are plotted again in Fig. 4 expressing the position of the resultant load as relative distance d/h. It can be noted that the results generally confirm the critical distance of 2.5 d for the minimum value of the shear strength.

In the same figures are also reported the shear strengths obtained for the load cases of uniformly distributed loads (dashed black lines).

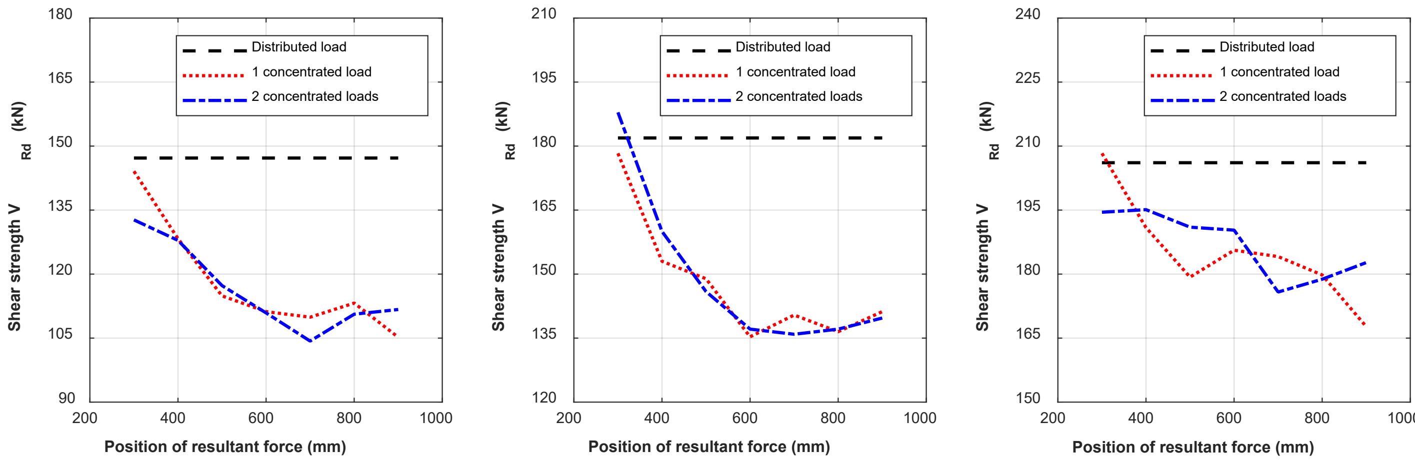

Fig. 3: Shear strength of HC slabs for absolute position of the applied loads: left 260 mm, centre 320 mm, right 400 mm.

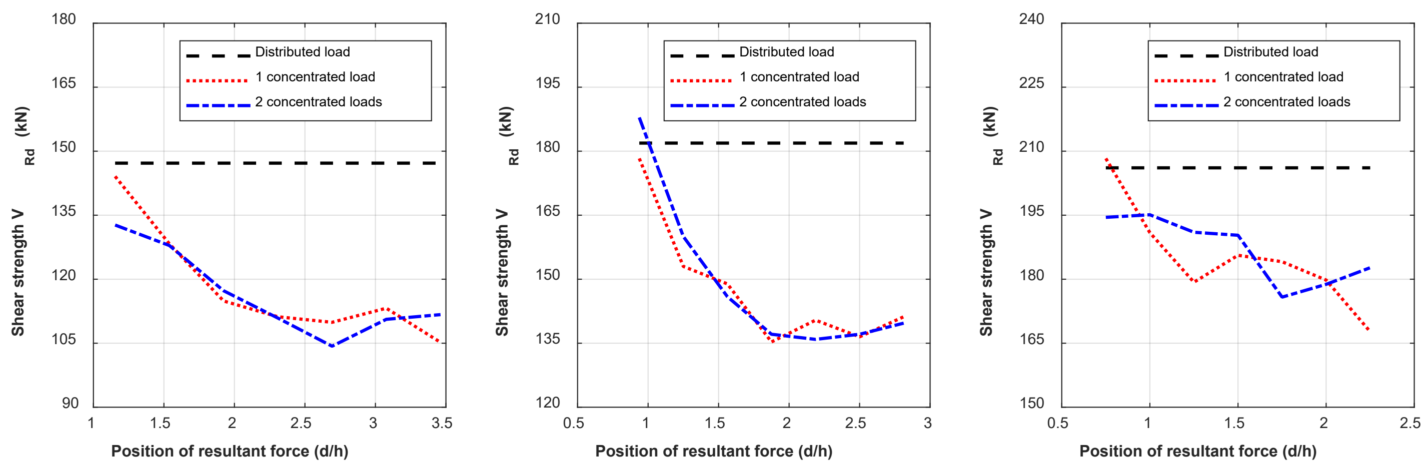

Fig. 4: Shear strength of HC slabs for relative position (d/h) of the applied loads: left 260 mm, centre 320 mm, right 400 mm.

3.3. Comments

As first comment, it can be observed that the shear strengths for the distributed loads are generally bigger that that obtained for the concentrated loads. In detail, the shear strengths for distributed loads are 41.1%, 34.4% and 22.9% bigger than the minimum strength for concentrated loads, respectively for the slabs of thickness of 260, 320 and 400 mm. This observation is not irrelevant as it happens very rarely (almost never) that the hollow core floors are loaded with relevant concentrated loads while the experimental verification load tests are carried out with concentrated loads. For these reason, alternative test methods or reduced partial safety factors could be used to consider the influence of the actual load pattern on the shear strength of the uncracked zones by bending moment.

A second remark arises from the cracking pattern observed at collapse through the numerical simulations. It can be inferred from the images shown in Figs. 5, 6 and 7. In these figures is shown the tensile damage parameter of the CDP constitutive law a few instances before the collapse. This parameter can assume values between 0 and 1 where 0 means no tensile damage and 1 represents the attainment of the ultimate tensile strain in the post peak branch of the concrete tensile stress-strain law.

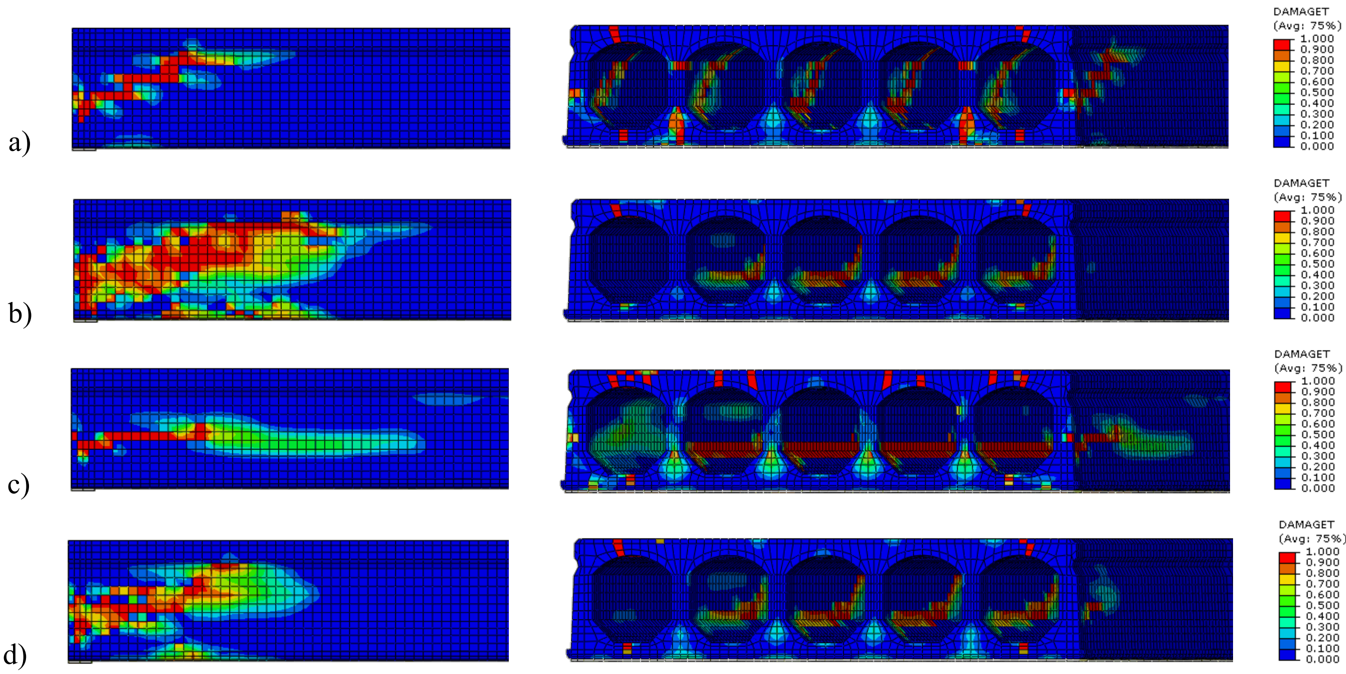

Fig. 5: Hollow core slab H26 - values of tension damage parameter T at collapse for different load conditions: 250-350 mm (a), 550-650 mm (b), 850-950 mm (c) and uniformly distributed (d).

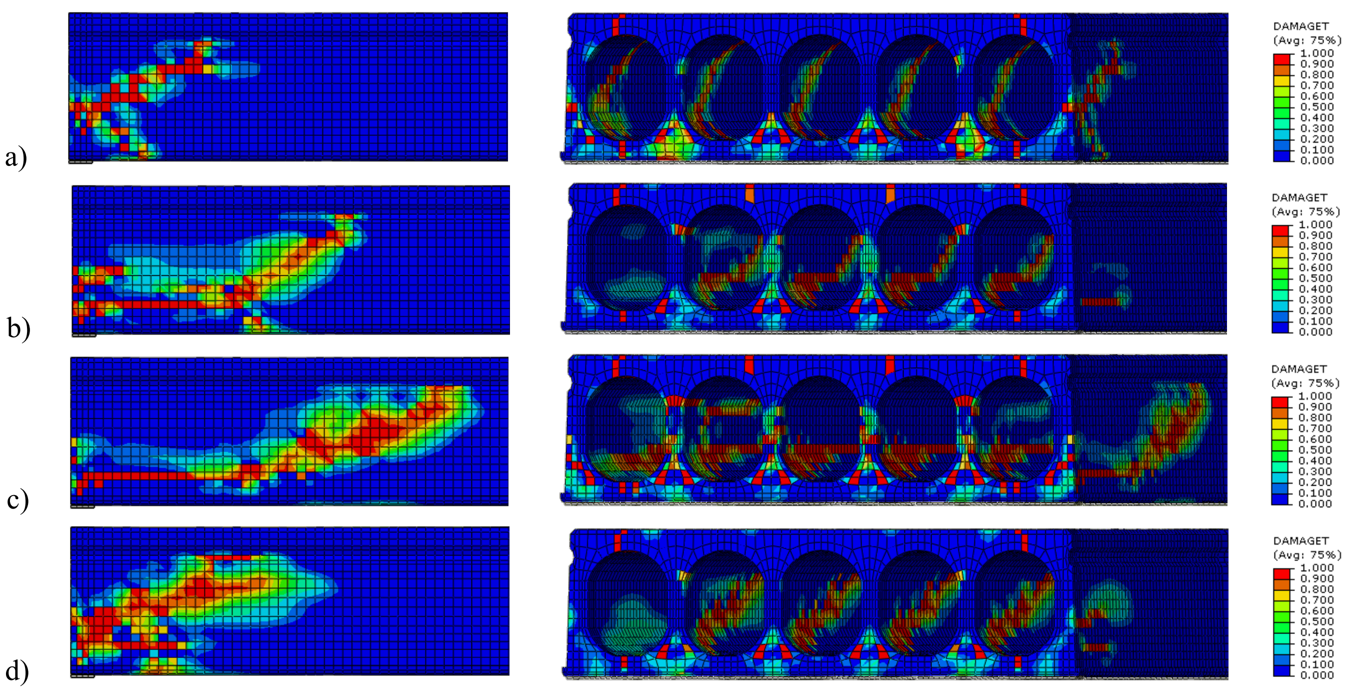

Fig. 6: Hollow core slab H32 - values of tension damage parameter T at collapse for different load conditions: 250-350 mm (a), 550-650 mm (b), 850-950 mm (c) and uniformly distributed (d).

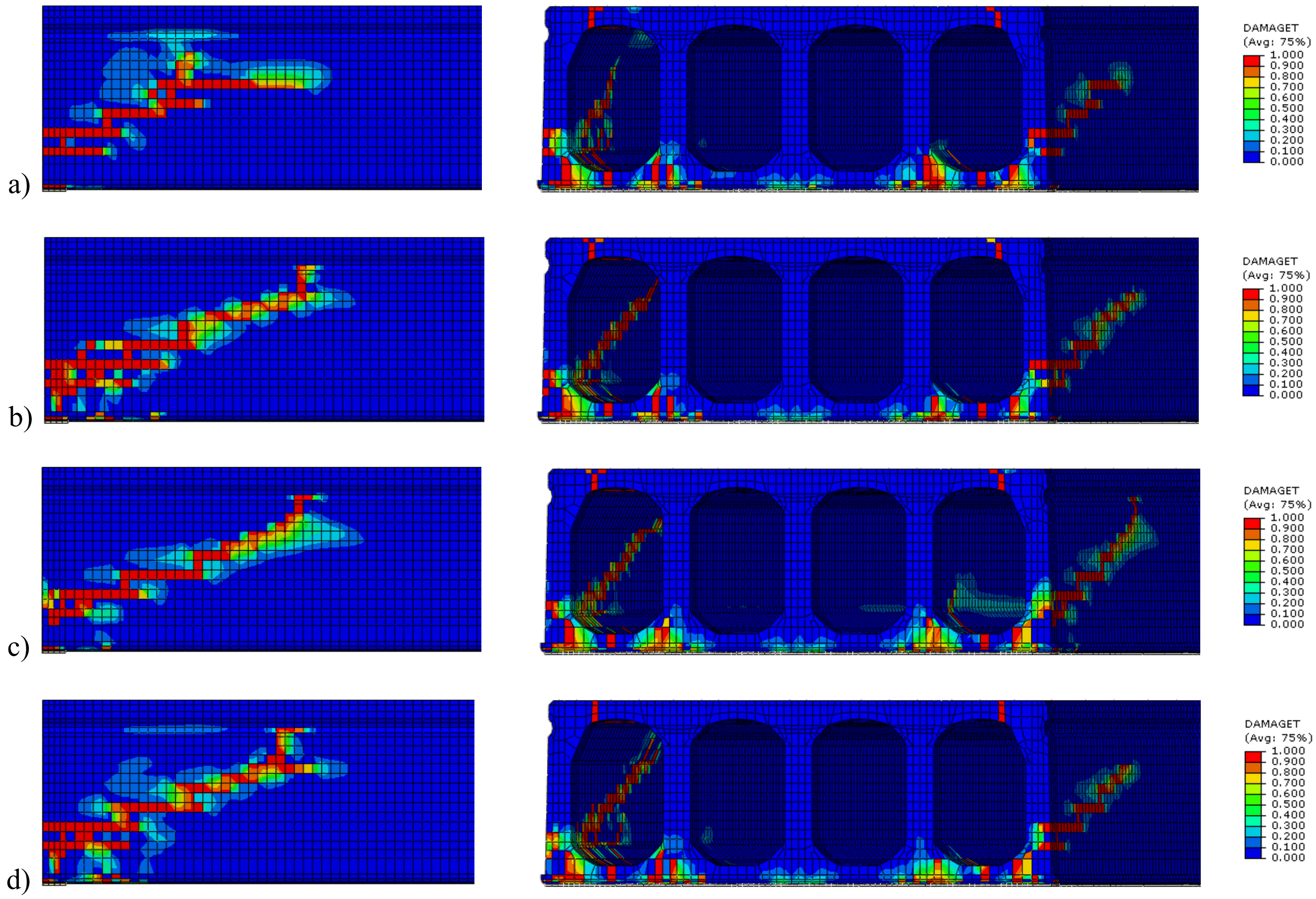

Fig. 7: Hollow core slab H40 - values of tension damage parameter T at collapse for different load conditions: 250-350 mm (a), 550-650 mm (b), 850-950 mm (c) and uniformly distributed (d).

From the figures it can be observed that web cracking can occur not simultaneously on all webs. Being the collapse due to concrete cracking of fragile type, only modest redistributions of stress can be hypothesized between cracked and uncracked webs at collapse. This suggests the importance of a correct optimization of the section, and in particular of the thickness of the webs, so that these thicknesses are proportional to the area of influence of each web.

5. Conclusion

In this study are reported the first results of numerical investigations carried out on the shear performance of HC slabs in the zones uncracked by bending moments. They can be resumed as follows:

1) the shear strength in the uncracked zones is strongly influenced by the type of applied load. In particular, it was observed that the shear strengths of hollow core slabs for distributed loads are always greater (between 22.9% and 41.1% for the investigated slabs) than those observed for concentrated loads;
2) the fragility of the collapse mechanism due shear of the individual webs does not allow the implementation of an effective transversal redistribution of the applied loads.

Based on these observations, it is suggested the use of test methods that reproduce the loading conditions of real structures or the adoption of reduced partial safety factors for shear collapse, and the development of optimized HC slabs cross section so as to make the web shear collapse of all webs simultaneous.

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