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Numerical analysis of ultra-high strength fibre-reinforced concrete slabs

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Abstract: Reactive Powder Concrete (RPC) is one the latest developments in concrete technology, also known as ultra-high-performance concrete (UHPC). It is characterised by the use of high cement content, with very high mechanical strength, high durability, in most cases, a quantity of steel fibres. A hollow core slab, also known as a void slab, hollow core plank, or simply a concrete slab is a precast concrete slab frequently used in the construction of floors in multi-story apartment buildings. The presence of holes in the reinforced concrete is necessary to act as ducts for services as well as having the structural purpose of reducing the weight of the slabs. This study examines previous experimental research results for 26 slabs in terms of examining the behaviours of reactive powder concrete slabs with longitudinal hollow cores of various sizes under various loading situations by changing the a/d ratio. The ANSYS computer program was used to investigate the behaviours of some of these slabs, and parametric studies were used to study the effects of the compressive strength of the concrete, types of support, and different steel reinforcement diameters. The results obtained using finite element solutions showed good agreement with experimental results.

1. Introduction:

Analysis and design of reinforced concrete slabs are interactive areas of research work. Reinforced concrete slabs were cast based on developed standards for the first time at the start of the twentieth century. These slabs are now familiar structural members, components of building structures that generally surround a space vertically. They can provide the lower support panels (floor) or top construction (roof) in any part of a structure **[1].**

RPC was invented in France in the early 1990s, and the first RPC structure in the world, the Sherbrook Bridge in Canada, was constructed in July 1997. RPC is an ultra-high-strength and high ductility cementitious composite with improved mechanical and physical characteristics. It is a special concrete improved at a microstructural level through accurate gradation of all particles in the mix to produce maximum density. The pozzolanic properties of highly refined silica fume and optimization of Portland cement chemical properties to create the highest strength hydrates is attributed to Pierre, Richard, and Marcel Cheyrezy **[2]**.

A hollow core slab (HCS) is a precast, or a prestressed concrete component with holes that spread throughout the span of the slab, to decrease weight and hence costs, as well as offering lateral advantages such as allowing passage of electrical or mechanical systems. These are mainly utilised as surface or roof deck systems, but HCS also have uses as members, partition sections, and bridge deck elements. The span of an HCS can equal 18 m without supports. Elements using pre-stressed HCS are often purpose designed for various applications requiring floor or roof systems. This method can be used preferentially in residential, commercial, or garage projects. Precast, prestressed HCS offers major structural member success through the operation of HSC, while demanding little material consumption **[3]**.

Fernando et al presented and developed an ideal model of steel fibre reinforced concrete (SRFC) to be used in plate elements **[4]**. These elements were investigated with regard to cracks, and the fibre content and the load system were considered variable in their investigation. The study used four different fibre contents and three different load systems. For each combination, three plates were tested, giving a complete sample of 36 units. The fibre contents were 0, 50, 70, and 90 kg of fibres/m^3 of concrete, and the load systems were as shown in Figure 1. The finite elements model showed good association with respect to the experimental results, suggesting that the model is capable of simulate the cracking process, which involves a fast stress decrease and a stress increase after cracking. The fibre addition does not characterise a relevant improvement in the development of the compression strength of the concrete.

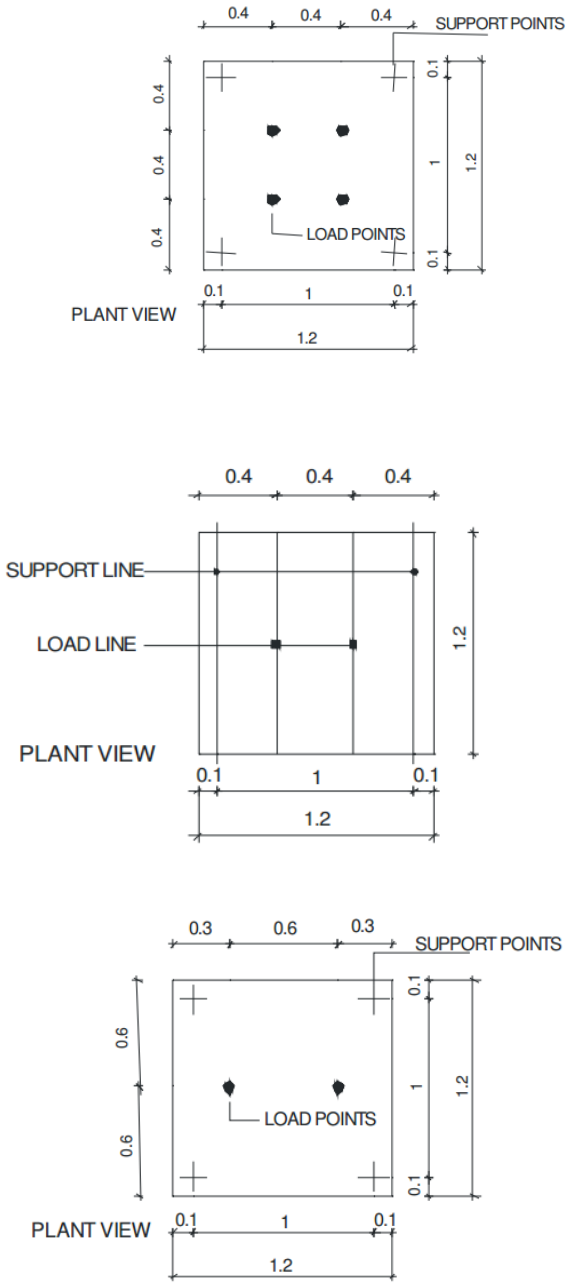

Figure 1 Types of loading on plate elements [4]

Hoogenboom developed a technique using finite element analysis for HCS flooring, and this technique may be crucial in case of relatively large floor openings **[5]**. The idea behind the technique was to create a computer program able to perform analysis that could be used as an assistive design tool. Several formulas are used to determine floor properties in the finite element solution. These formulas are used to calculate the degree of stress recovery, and they were established by the use of the section method of analysis, which determines moments and forces in critical parts of the floor. These stresses are then compared to floor material strength at these parts of the floor. The study of hollow-core slab floors revealed that large openings are possible without the need for additional beams and columns. Similarly, **Mahdi** performed a non-linear analysis on hollow reinforced concrete slabs using the finite element method to examine plate bending and beam elements **[6]**. The study divided the HCS into two chief parts, the hollow plates that represent the top and bottom flanges and the stiffening beams which represent the vertical webs between them. A computer program was modified to analyse different reinforced and pre-stressed hollow slabs, and the finite element solutions were compared with the available experimental results to prove the potential of computational non-linear models in terms of obtaining results close to the experimentally obtained results. The behaviour of hollow reinforced and pre-stressed slabs in response to changes in the model and material parameters was determined through parametric studies when the load-deflection response was obtained. These parameters included the influence of concrete strength, pre-stressing tendon amounts, existence of holes, hole size, hole shape, and failure concrete crushing strain. Generally, an acceptable level of match between the results obtained from finite element analysis and the investigational work was found.

2. Experimental programme

The current research included testing two solid slabs and twenty-four hollow-core slabs divided into four groups, as shown in Table 1 [7]. The first group had hollow-cores and were of diameter 75 mm with bottom reinforcement; the second group had hollow-cores and were of diameter 75 mm with double reinforcement (bottom and top); the third group had hollow-cores and were of diameter 100 mm with bottom reinforcement; while the last group had hollow-cores and were of diameter 100 mm with double reinforcement (bottom and top). All specimens had the same lengths, thicknesses, and widths, 1,000 mm, 200 mm, and 600 mm, respectively.

Table 1 Details and results of tested slab specimens [7]

Slab designation	**Ultimate load (kN)**	**Ultimate deflection (mm)**	**a/d ratio**	**V_f steel fibres %**	**Reinforcement details**	**No. of cores**	**Core Size (mm)**	**Opening size and location**	**Opening shape**
S10	360	11	1.74	1%	bottom bars	2	75	-	-
S11	465	12	1.74	1%	bottom bars	-	-	Solid	-
S12	320	10	1.74	1%	bottom bars	3	75	-	-
S13	391	11.5	1.45	1%	bottom bars	2	75	-	-
S14	347	10.4	2	1%	bottom bars	2	75	-	-
S15	380	11.5	1.74	1.5%	bottom bars	2	75	-	-
S16	340	10.7	1.74	0.5%	bottom bars	2	75	-	-
S20	410	12.5	1.74	1%	bottom and top bars	2	75	-	-
S21	495	13	1.74	1%	top and bottom bars	-	75	Solid	-
S22	284	8.5	1.74	1%	bottom and top bars	2	75	133(centre)	square
S23	357	9.5	1.74	1%	bottom and top bars	2	75	133(edge)	square
S24	290	9	1.74	1%	bottom and top bars	2	75	150(centre)	circle
S25	270	8	1.74	1%	bottom and top bars	2	75	150(edge)	circle
G26	350	11.2	1.74	1%	bottom and top bars	3	75	-	-
S30	345	10.2	1.74	1%	bottom	2	100	-	-
S32	310	9.5	1.74	1%	bottom	3	100	-	-
S33	356	10.9	1.45	1%	bottom	2	100	-	-
S34	330	10.5	2	1%	bottom	2	100	-	-
S35	359	11	1.74	1.5%	bottom	2	100	-	-
S36	315	8.5	1.74	0.5%	bottom	2	100	-	-
S40	400	12.1	1.74	1%	bottom and top bars	2	100		
S42	300	10.3	1.74	1%	bottom and top bars	2	100	133(centre)	square
S43	395	11.5	1.74	1%	bottom and top bars	2	100	133(edge)	square
S44	320	12	1.74	1%	bottom and top bars	2	100	150(centre)	circle
S45	389	11.5	1.74	1%	bottom and top bars	2	100	150(edge)	circle
S46	330	11	1.74	1%	bottom and top bars	3	100		

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3. Finite Element Analysis

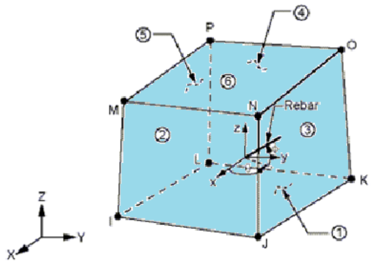
The representation of slab samples was achieved using three kinds of elements. The first one was used for the concrete, the reinforcing steel bars were formed by the second, and the third represented the varying proportions of steel plate and rubber used for cushioning.

SOLID65 is used for the 3-D modeling of solids with or without reinforcing bars (rebar). The solid is capable of cracking in tension and crushing in compression. The element is defined by eight nodes with three degrees of freedom at each node.

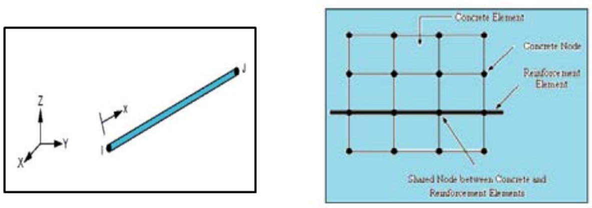
LINK180 is a spar which may be used in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, and springs. The 3-D spar element is a uniaxial tension compression element with three degrees of freedom at each node:

SOLID185 is used for the 3-D modeling of solid structures. The element is defined by eight nodes with three degrees of freedom at each node

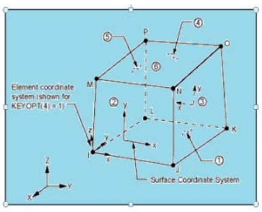
Figure 2 shows the geometry for these materials [8].



a- Geometry of SOLID 65



b- LINK180 geometry and discrete models of reinforcement



c- Geometry of solid 185

Figure 2 Geometry of materials [8]

3.1 Hollow core slab with one layer of reinforcement

In finite element analysis, only one quarter of slab (S30) of [7] was taken into account. The slab has hollow cores (two cores of diameter 100 mm, bottom reinforcement only, and an a/d= 1.75). Figure (3) shows that the load deflection behaviour for this hollow slab (S30) using ANSYS of φ8 mm was decreased by about 5.5% and 4.76%, respectively when compared with the experimental version [7] of the same specifications. The dimensions of slab are 1000 x 600 x 200 mm.

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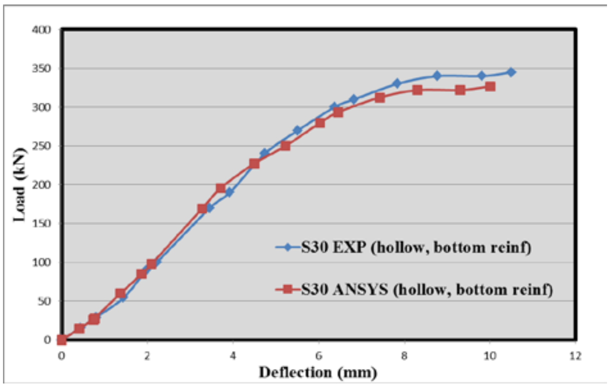

Figure 3 Comparison between load-deflection curves for slab S30 (experimental and theoretical) [7]

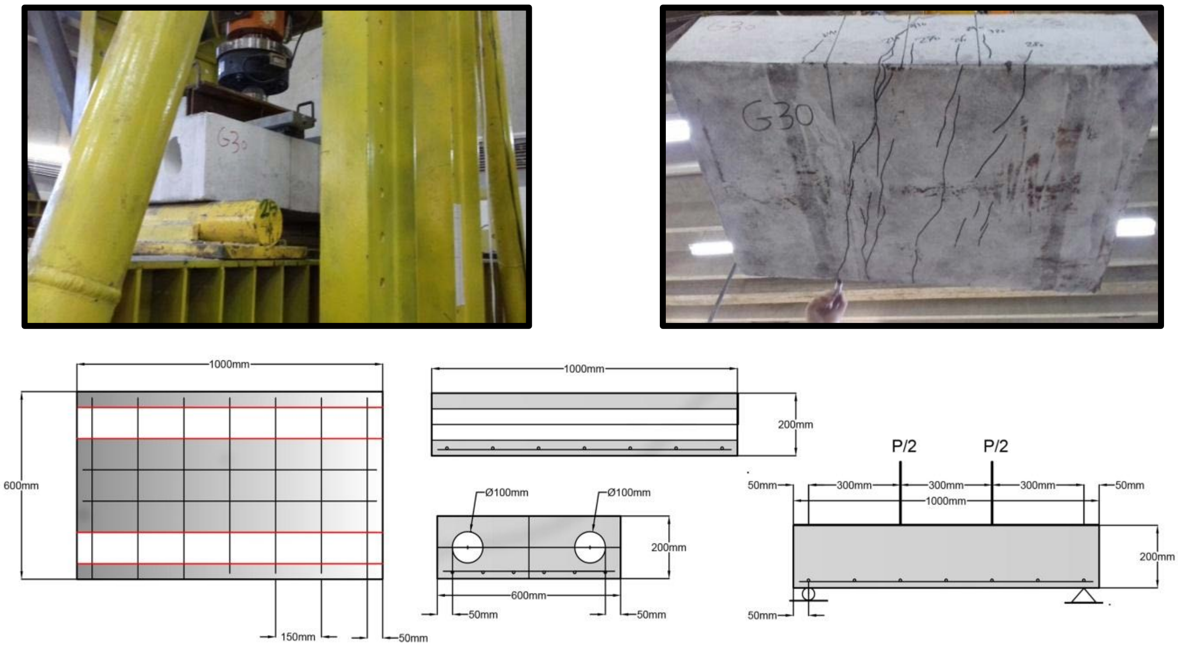

Figure 4 Details of slab specimens, loading arrangement, and reinforcement details for hollow core with one layer of reinforcement

3.1.1 *Effect of steel reinforcement diameter*

Various values of steel reinforcement diameter were used, namely φ6, φ8, φ10, and φ12 mm; these were compared with the φ8 mm used in experimental work on slab (S30), which has bottom reinforcement only. Figure (5) shows the load deflection curves for different steel areas. Table (2) shows the ultimate load and ultimate deflection for the hollow slab (S30)

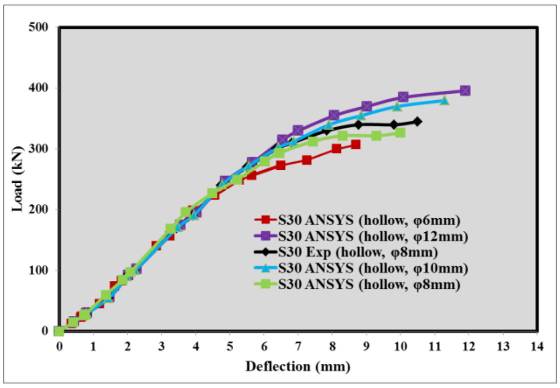

Figure 5 Effect of steel reinforcement diameter on load-deflection curves for hollow longitudinal core slab (S30) [7]

Table 2 Ultimate loads for slab S30 with different steel reinforcement diameters (φ6, φ8, φ10 and φ12 mm)

Slab designation	Steel reinforcement diameter (mm)	Ultimate load test (kN)	Ultimate deflection (mm)	Load percentage compared with exp φ8 (%)	Deflection percentage compared with exp φ8 (%)
S30	8 mm (Exp)	345	10.5	-	-
	8 mm (ANSYS)	326	10	-5.5	-4.76
	10 mm (ANSYS)	380	11.3	10.14	7.61
	12 mm (ANSYS)	396	11.9	14.7	13.33
	6 mm (ANSYS)	307	8.69	-11	-17.23

3.1.2 Effect of compressive strength of concrete

Two values of concrete grade were taken, 110 and 130 MPa, and these were compared with concrete grade 85 MPa (Exp). The hollow core slab with shear span ratio a/d equivalent to 1.75 with two longitudinal cores with diameter 100 mm was selected to examine the influence and impact of the grade of concrete on the load-deflection behaviours. Figure (6) shows the load deflection curves for different compressive strengths.

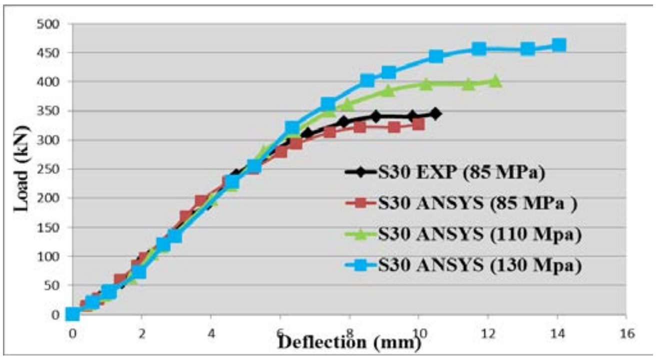

Figure 6 Effect of compressive strength of concrete on load-deflection curves for hollow slab S30 [7]

3.1.3 Effect of boundary conditions on load-deflection behaviours of slab (S30)

Different types of support for slab S30 (hinged and fixed) were studied, and the behaviours compared with simply supported slabs as in the experimental work. The hollow core slab with shear span ratio a/d equivalent to 1.75 was selected to examine the influence and impact of type of support on the load-deflection behaviours. Figure (7) shows the load deflection curves for different boundary conditions.

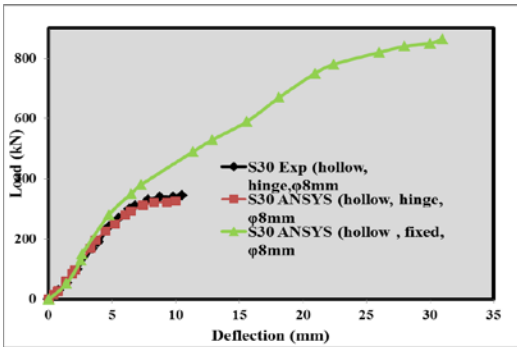

Figure 7 Effect of type of support on load-deflection curves for hollow core slab (S30) [7]

3.2 Hollow core slab S40 with two steel reinforcement layers

For finite element analysis, only one quarter of slab (S40) was selected; here, the slab has a hollow core with bottom and top reinforcement, two cores of diameter 100 mm and an a/d=1.75. Figure (8) shows that the ultimate load and ultimate deflection for hollow slab (S40) estimated by ANSYS at φ8 mm decreased by about 6% and 6.4% respectively when compared with experimental work of the same specifications [7].

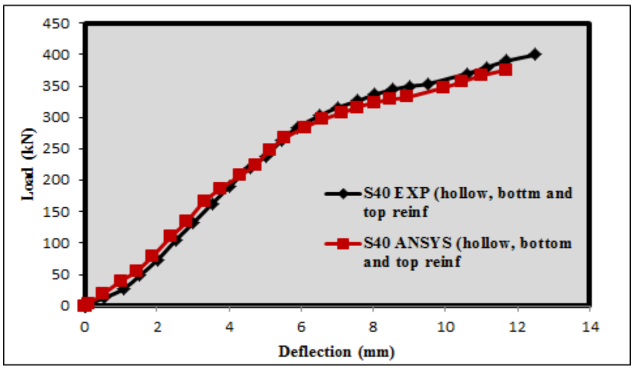

Figure 8 Comparison between load-deflection curves of slab S40 (experimental and theoretical) [7]

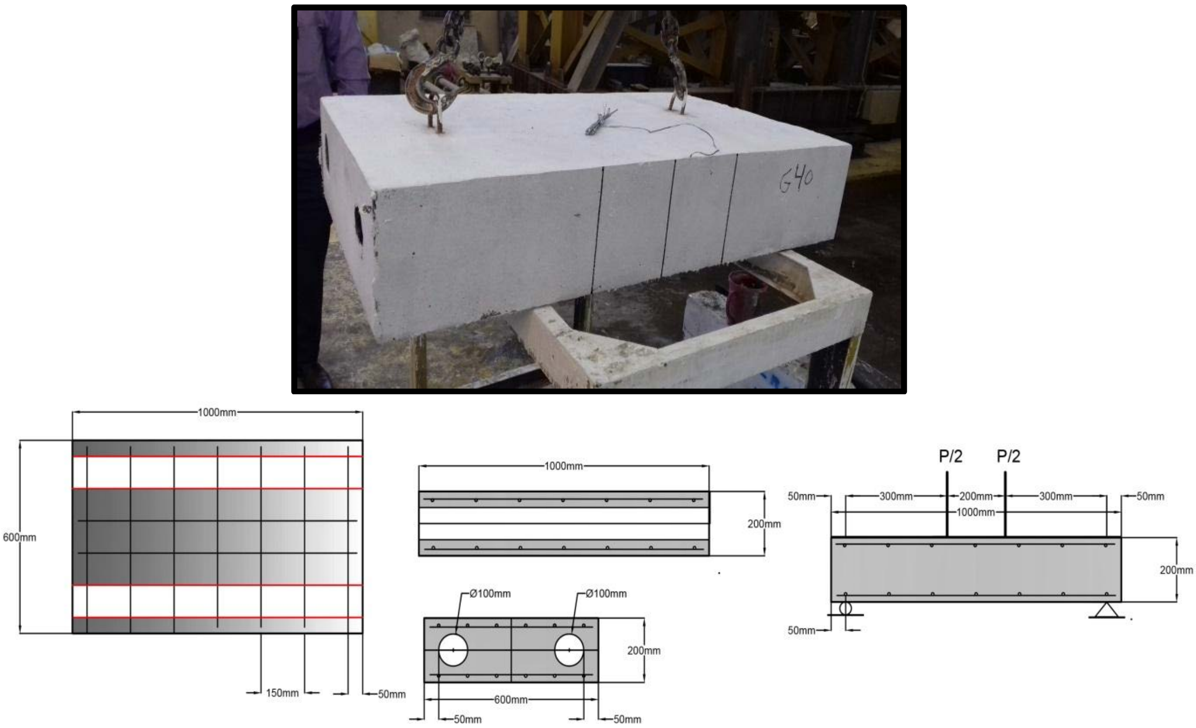

Figure 9 Details of slab specimens, loading arrangement, and reinforcement details for hollow core with two-layer reinforcement

3.2.1 Effect of Steel Reinforcement diameter

Various values of steel reinforcement area, φ6, φ8, φ10, and φ12 mm, were taken and compared with experimental work on slab (S40) which had bottom and top reinforcement. This group consists of UHS slabs with different steel reinforcement diameters, enabling examination of the influence and impact of reinforcement on load-deflection behaviours. Figure (10) shows the load deflection curves for different steel areas, while table (3) shows the ultimate load and ultimate deflection for the hollow slab (S40).

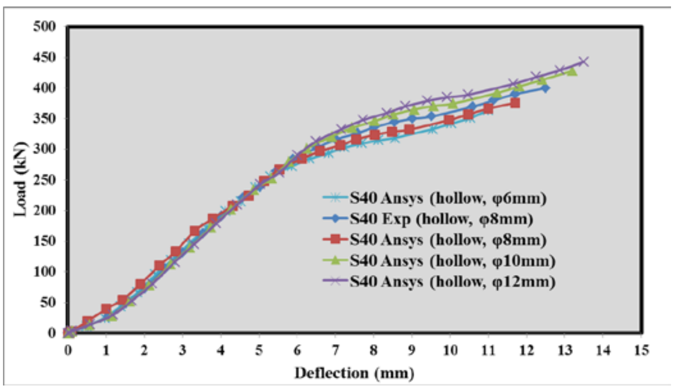

Figure 10 Effect of steel reinforcement diameter on load-deflection curves for hollow core slab (S40) [7]

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Table 3 Ultimate loads for slab S40 with different steel reinforcement diameter (φ6, φ8, φ10, and φ12 mm)

Slab designation	Steel reinforcement diameter (mm)	Ultimate load (kN)	Ultimate deflection (mm)	Load percentage compared with exp φ8 (%)	Deflection percentage compared with exp φ8 (%)
S40	8 mm (Exp)	400	12.5	-	-
	8 mm (ANSYS)	376	11.7	-6	-6.4
	10 mm (ANSYS)	428	13.2	7	5.6
	12 mm (ANSYS)	443	13.5	10.75	8
	6 mm (ANSYS)	364	11	-9	-12.5

3.2.2. Effect of compressive strength of concrete

Two values of concrete grade were taken, 110 and 130 MPa, and compared with the compressive strength of the tested slab with grade 85 MPa. A slab with shear span ratio a/d equivalent to 1.75, bottom and top reinforcement, and a longitudinal core diameter of 100 mm was selected to examine the influence and impact of the grade of concrete on load-deflection behaviours. Figure (11) shows the load deflection curves for different compressive strength.

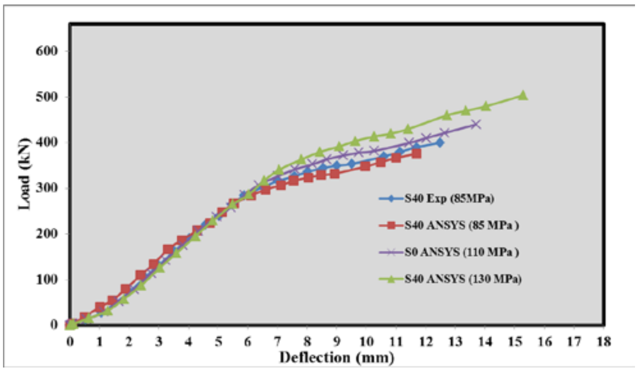

Figure 11 Effect of compressive strength of concrete on load-deflection curves for hollow slab (S40) [7]

3.2.3 Effect of boundary conditions on load-deflection behaviours

Different type of support for slab (S40) (hinge and fixed) were examined and the behaviours compared with simply supported beams used in the experimental work. The slab with shear span ratio a/d equivalent to 1.75 and bottom and top reinforcement was selected to examine the influence and impact of type of support on the load-deflection behaviours. Figure (12) shows the load deflection curves for different boundary conditions.

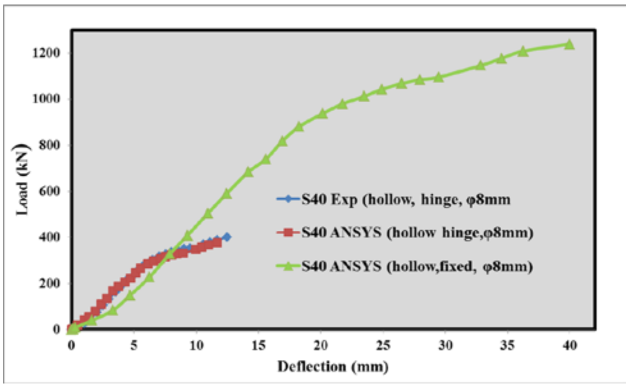

Figure 12 Effect of type of support on load-deflection curves for hollow longitudinal core slab (S40) [7]

4. Conclusions

1. The ultimate loads for slabs S30 (ANSYS) of φ8 and φ6 mm were decreased by about 5.5 and 11% when compared with slab S30 (Exp), and the ultimate loads of slabs S30 (ANSYS) with φ10 and φ12 mm were increased by about 10.14 and 14.7%, respectively, when compared with slab S30 of φ8 mm (Exp). The ultimate deflections for slab S30 (ANSYS) of φ8 and φ6 mm were decreased by about 4.76 and 17.23% respectively, and the ultimate deflections for slabs S30 (ANSYS) of φ10 and φ12 mm were increased by about 7.61 and 13.33%, respectively.
2. The ultimate load for slab (S30) (ANSYS) of grade 85 MPa was decreased by about 5.5% when compared with slab S30 (Exp), those for and slab S30 (ANSYS) of grade 110 and 130 MPa were increased by about 16.3 and 33.9% respectively when compared with slab S30 (Exp). The ultimate deflections for slab S30 of grade 110 MPa and grade 130 MPa were increased by about 16.19 and 34.28, respectively.
3. For the fixed type of support, the ultimate load is increased for slab S30 (ANSYS) of grade 85 MPa by about 150.43% when compared with slab S30 (Exp). The ultimate deflection for slab S40 (ANSYS) with fixed support increased by about 220% compared to slab S11 (Exp) with simple support.

5. References

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