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Waffle Slab with Eccentric Opening Externally Strengthened by Basalt Textile Reinforced Mortar

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Abstract

This study investigates the behaviour of two-way waffle slabs that contain an eccentric opening. These slabs were externally strengthened by the basalt textile reinforced mortar (BTRM) technique under simply supported boundary conditions. The dimensions of the samples were (1050 ×1050 mm), and the precise topping thickness was (50 mm), while the joist dimension was (100 × 50 mm). Steel reinforcement was mesh at the top (ϕ6 mm @ 75 mm c/c), and the bottom of the joists contained (1 ϕ8 mm).

The strengthening process was carried out on the ribs that were cut by square and circular opening, and the result revealed that warping the catted ribs by the basalt textile reinforced mortar technique enhanced flexural strength and significantly increased ductility.

Keywords: investigates, Reinforcement, strengthening

1. **Introduction**

Due to the large spans provided by waffle slabs, introducing an opening that leads to cutting the main joists became a major critical that needs further exploration regarding shear failure behaviour in this zone[1]. The strengthening process using FRP, which implemented epoxy as the primary bonding material, has been the primary strengthening process for the past decades[2-4]. Inorganic matrices that mainly provided cement-based mortars with a fibre-containing open mesh configuration as textile-reinforced mortar (TRM) were also investigated to overcome the drawbacks[5]. Moreover, this solution was an alternative to FRP and more sustainable and friendly to handle within construction sites. In addition, the ability to handle large fire degrees or implement in wet conditions[6]. [7]looked into how the rib layout and the ratio of waffle slab thickness to rib height affected the flexural behaviour. Reducing the thickness of the upper panel could more severely compromise the integrity of the waffle slab than reducing the number of ribs [8]. Waffle slab joist spacing and total load-carrying capacity were found to be inversely related [9].

The stiffness and punching shear strength of the waffle slabs subjected to eccentric loading were enhanced by giving the r ibs more depth and thickness [10]. [11] studied waffle slabs experimentally to determine the ideal joist spacing, and the findings indicated that the ideal joist spacing varied based on panel dimensions.

In this research, an experimental study on the structural behaviour of a two-way waffle slab containing an eccentric opening was externally strengthened by the basalt textile reinforced mortar (BTRM) technique under the effect of uniform distributed load and simply supported boundary conditions.

2. Experimental program

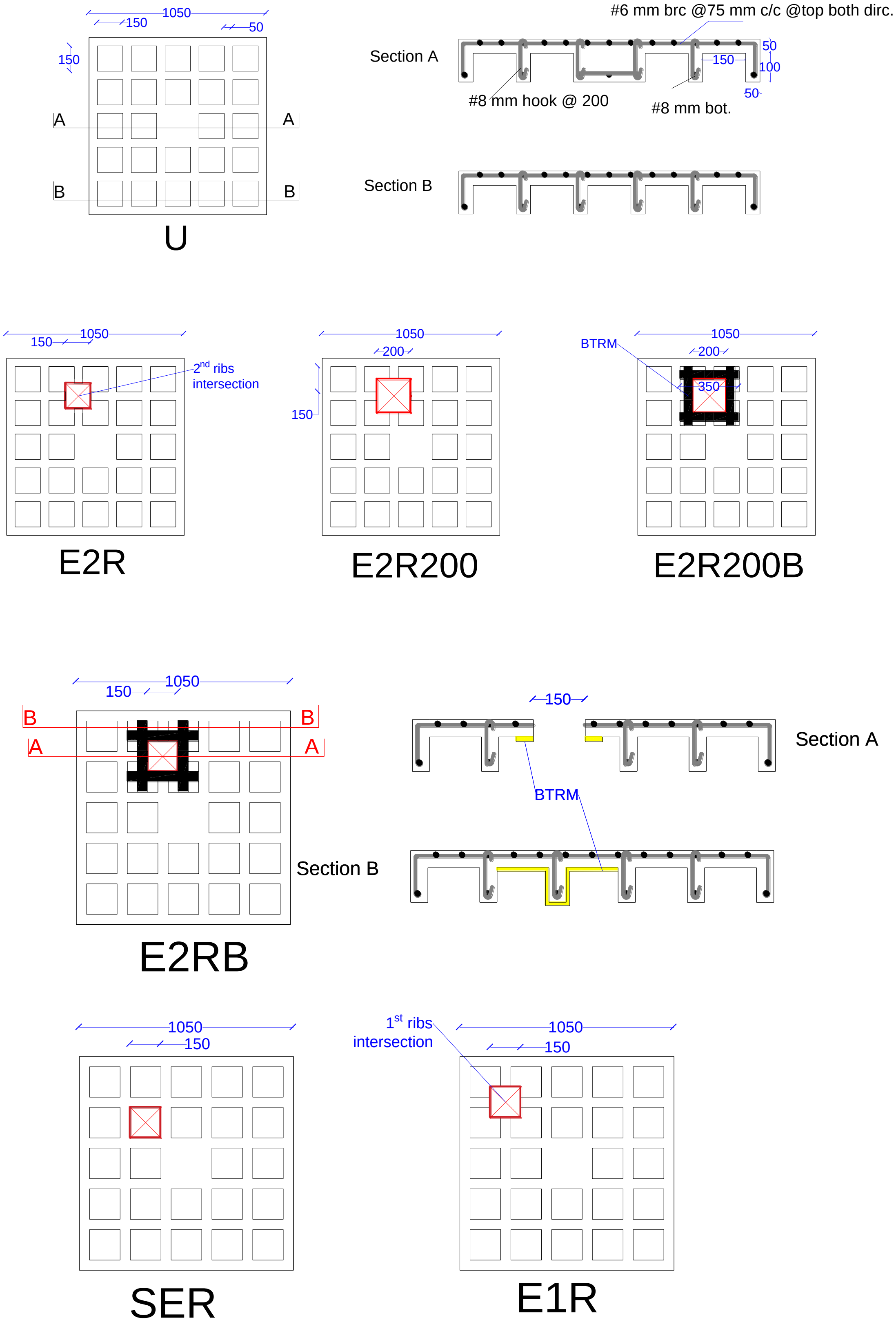
This study involves ten specimens; the overall dimensions were (1050 ×1050 mm) and precise topping thickness (50 mm), while the joist dimension was (100 × 50 mm). Steel reinforcement was arranged orthotopically, consisting of mesh at the top (ϕ6 mm @ 75 mm c/c), and the bottom of the joists contained (1 ϕ8 mm) as shown in fig. (1).

The slabs were classified into control without opening (U) and two with (200 mm) square opening at the second rips intersection close to the edge, the first one without any strengthening (E2R200), and the other had a BTRM sheet on the joist around the open (E2R200B). specimens (E2R and E2RB) were the same as (E2R200 and E2R200B) except That had A (150 mm) opening.

Another slab contains a square (150 mm) opening positioned at the intersection of the first ribs (E1R). An opening without damaging ribs was investigated in (SER) in the first waffle bay from the solid centre.

A circular opening that had a (150 mm) diameter was investigated in three waffle slabs (E1C, E2C and E2CB) that had the precisely same properties as slabs (E1R, E2R, and E2RB) respectively.as shown in Fig. (1).

All slabs were subjected to a uniform distributed load under simply supported conditions from the four edges. Table (1) illustrates the slabs geometry.



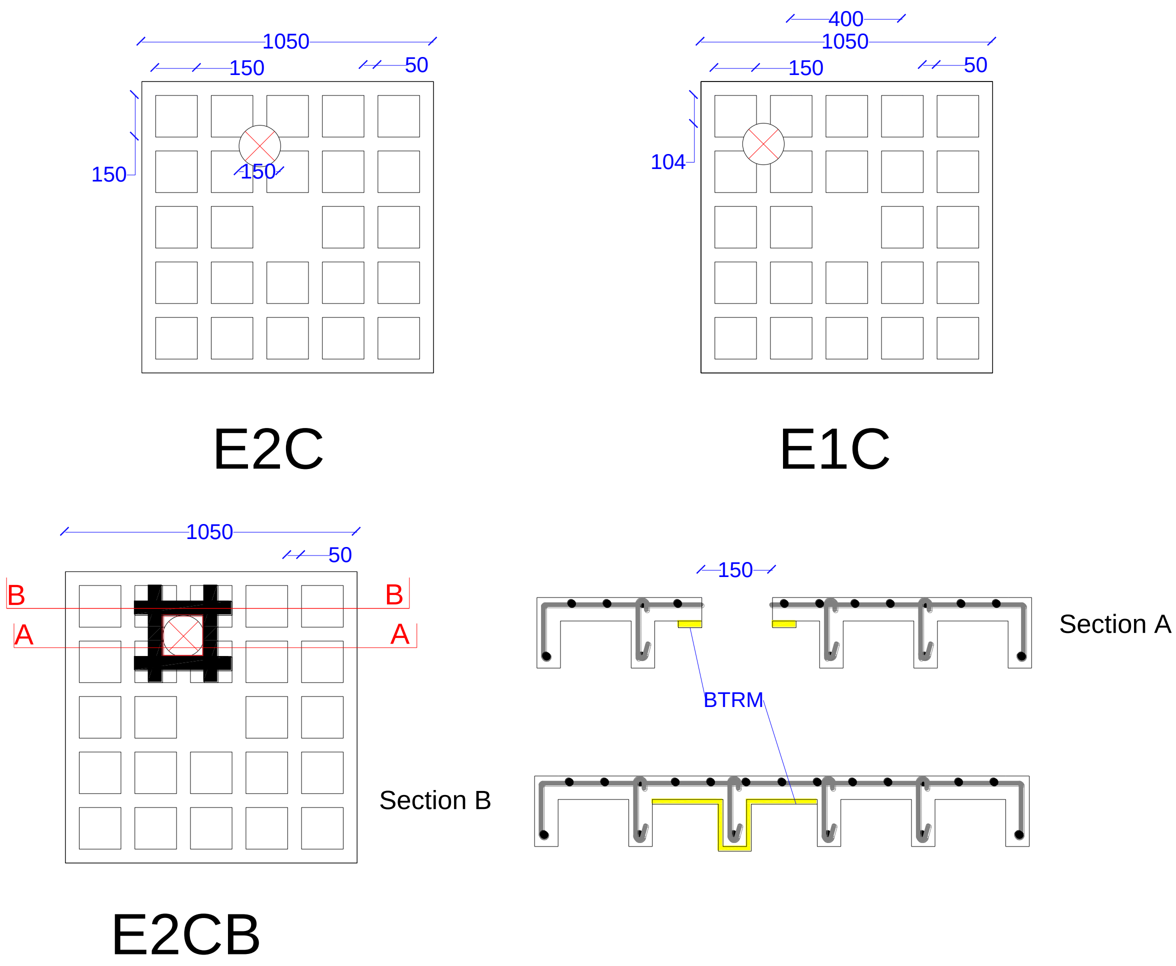


Fig.1 Slabs geometry

In the casting process of the waffle slab, normal concrete with (f'c =35 Mpa) and moisture cured until 28 days before strengthening. Steel rebar yielding and tensile strengths are shown in table (2)

Table 1. Specimens details

Specimens	**Opening size (mm)**	**Opening shape**	**Opening position**	**Strengthening**
U	----	----	----	----
E2R200	200 x 200	Square	2nd ribs intersection	----
E2R200B	200 x 200	Square	2nd ribs intersection	BTRM
E1R	150 x 150	Square	1st ribs intersection	----
E2R	150 x 150	Square	2nd ribs intersection	----
E2RB	150 x 150	Square	2st ribs intersection	BTRM
SER	150 x 150	Square	Corner bay from the solid centre	----
E1C	150	Circle	1st ribs intersection	----
E2C	150	Circle	2nd ribs intersection	----
E2CB	150	Circle	2nd ribs intersection	BTRM

Table 2. Steel reinforcement properties

Bar diameter	Fy (Mpa)	Fu (Mpa)
6	350	470
8	430	546

The formwork was prepared, and pressurized cork cubes made the waffle bays, as shown in Fig. (2).

Fig.2 Waffle formwork

Cement-based polymer-modified mortar (Cermirep R4 T) was used as an adhesive in basalt textile reinforced mortar (BTRM) with high compressive and adhesion stresses, This fibre-reinforced mortar combines specialised cements, high-purity silica sand, and fibre-reinforced additives as listed in Table 3. At the same time, basalt mesh consists of a (5 mm) square textile with high tensile stress fibre, which has properties in Table 4.

Before applying mortar, the concrete surface was rubbed until a rough surface was achieved, and then (50 mm) strips were submerged into the mortar see Fig. (3). Then, moisture curing (28 days) took place for the mortar.

Table 3. Mortar properties

Dry density	Compressive strength (1 day)	Compressive strength (28 days)	Flexural Strength (28 days)	Tensile Adhesion Strength	Modules of elasticity
1.75 kg/l	18 MPa	65 MPa	≥10 MPa	≥ 2.0 MPa	34.2 GPa

Table 4. Basalt mesh properties

Mesh size	Tensile Strength	Ultimate strain	Tensile modulus of elasticity
5 x 5 mm	830 MPa	2.8 %	29 GPa

Fig.3 BTRM installation

4. Results and discussion

Table (5) illustrates the experimental results of the tested specimens. The observed cracking load, maximum loading capacity, failure mode, and maximum deflection were listed. Generally, flexural failure with rib cracking was the dominant behaviour for all slabs.

Table 5. Experimental results

specimens	Cracking load Pcr (kN)	Failure load Pu (kN)	Decreasing in loading capacity %	Crack width at 0.65 Pu (mm)	Max crack width (mm)	Max deflection (mm)	failure mode
U	85	405	-----	0.38	4.03	21.07	flexural failure with ribs cracking
E2R200	56	293	27.65	0.36	2.7	16.47	
E2R200B	67	318	21.48	0.28	3.1	21.52	
E1R	74	319	21.23	0.36	3.4	18.89	
E2R	70	307	24.20	0.31	3	18.57	
E2RB	77	345	14.81	0.35	4.7	24.95	
SER	80	384	5.19	0.38	3.5	24.88	
E1C	77	325	19.75	0.27	3.1	18.68	
E2C	73	313	22.72	0.37	2.7	18.37	
E2CB	78	357	11.85	0.33	2.4	24.3	

Cracks pattern

The two-way waffle slabs' cracking performance followed the general deformation structural effect and could be divided into three main stages. At the start of applied loading (concentrated and uniformly distributed), elastic deformation dominates the slabs until the first crack appears on the middle zone ribs close to the solid portion.

In the elastoplastic stage, the cracks start to spread to cover most of the ribs and keep widening until a plastic stage combines fast-spreading and wider cracks than previous stages.

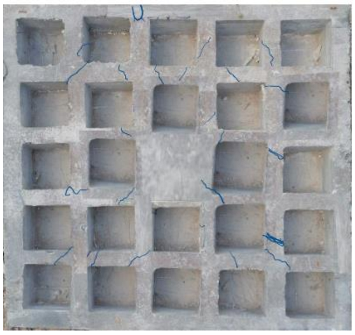
The test results showed that the opening position was the most effective parameter for cracking patterns for the same concrete materials. the cracks spread toward the centre and rarely can be recognised near the edges opposite the first ribs intersection opening (E1) slabs (E1R and E1C).

Since cutting the ribs influenced tensile stress transfer, the first cracks hold their positions in the central zone. Regarding the second rib (E2) intersection opening (E2R and E2C), the effect was more considerable than the (E1) opening, resulting in a more unsymmetric distribution of cracks around the opening zone.

The slab (SER), which had an opening on the first waffle bay near the solid centre, was surrounded by ribs and performed similarly to the control slab (U). It had a higher loading capacity than all other opening positions, with cracks spreading and a larger width.

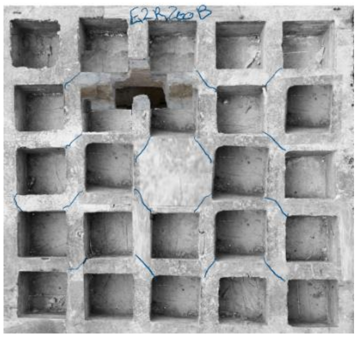
Increasing the opening size from (150x150) to (200 x 200) mm2 reduced structural capacity, and the crack formation was considerably similar in both cases, except that E2R formed a wider crack than E2R200 because of the earlier failure of the last slab.

circular shape opening (E1C and E2C) slabs showed significant cracks forming that had spread all over the bottom ribs, but square opening slabs (E1R and E2R) had a diagonal cracks band connecting to the opening four edges and larger width compared to circular one. The cracked specimens are shown in Fig. (4), and flexural failure with cracked ribs was recorded for all the slabs.



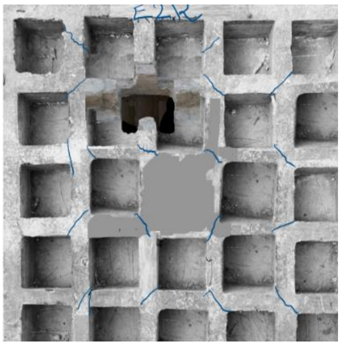
U

E2R200



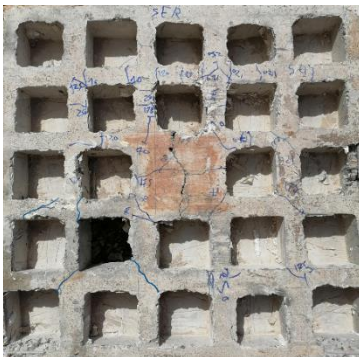
E2R200B

E1R



E2R

E2RB



SER

E1C

E2C

E2CB

Fig. 4 Cracked slabs

Cracks width

Fig. 5 illustrates the curves of maximum crack width against load for all slabs, demonstrating the progression of cracks from their initial appearance to failure. The control slab U exhibited a higher envelope, while similar behaviour was recorded for SER, which differed from the other slabs with openings. However, E2RB showed the maximum crack width due to the increased energy absorption from BTRM strengthening.

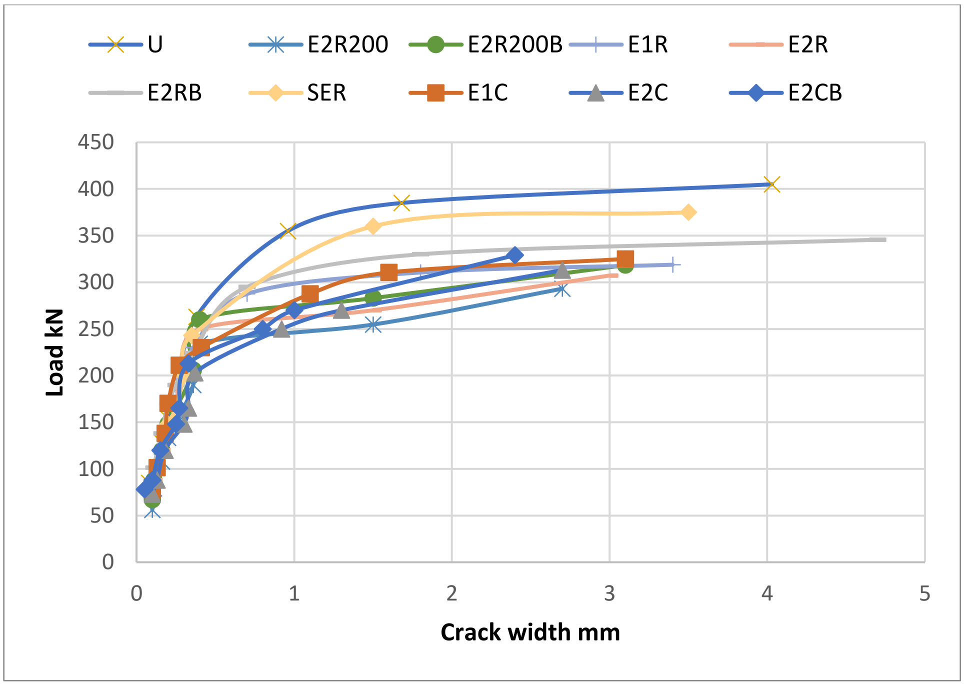


Fig. 5 max cracks width

Load deflection behavior

The load-deflection curves in Fig. (6) exhibited an initial elastic behaviour, after which the three-phased curves were influenced by the first cracking occurring at (19.11-23.7) % of the failure load. Once the steel reinforcement reached yielding stress, the plastic phase, the final phase in slabs, became dominant, leading to a rapid increase in displacement data records with an insignificant load rise.

Test results do not reveal a considerable difference between circular and square openings regarding ultimate loads and their corresponding deflection. Although there was a (1.9 and 1.93 %) increase in loading capacity for slabs (E1C and

E2C) above square opening waffles (E1C and E2C), larger-scale studies must be carried out to thoroughly examine the effects of opening shapes on waffle slabs.

The opening position seems to be a substantially effective parameter for loading capacity for the tested specimens. Changing the position of the openings (with the same size) from the second to first ribs intersection was combined with significant loading capacity raising and a considerable deflection increase, which achieved more ductility. Waffle slabs (E1C and E1R) had higher failure loads than (E2C and E2R) by (3.9 % and 3.8 %).

Cutting the opening surrounded by ribs in the slab, SER was sufficient to prevent slab capacity deterioration, with only a (5.18 %) lower failure load from solid slab U. Other slabs recorded a lower percentage (11.85 % to 27.6 %).

Reducing the opening size from 200 mm to 150 mm improved the load capacity of waffle slabs and enhanced the final deflection. For non-strengthened slabs, E2R had a higher failure load of 4.78 % than E2R200. Implementing BTRM strengthens the difference between E2RB and E2R200B, which is 8.49 %.

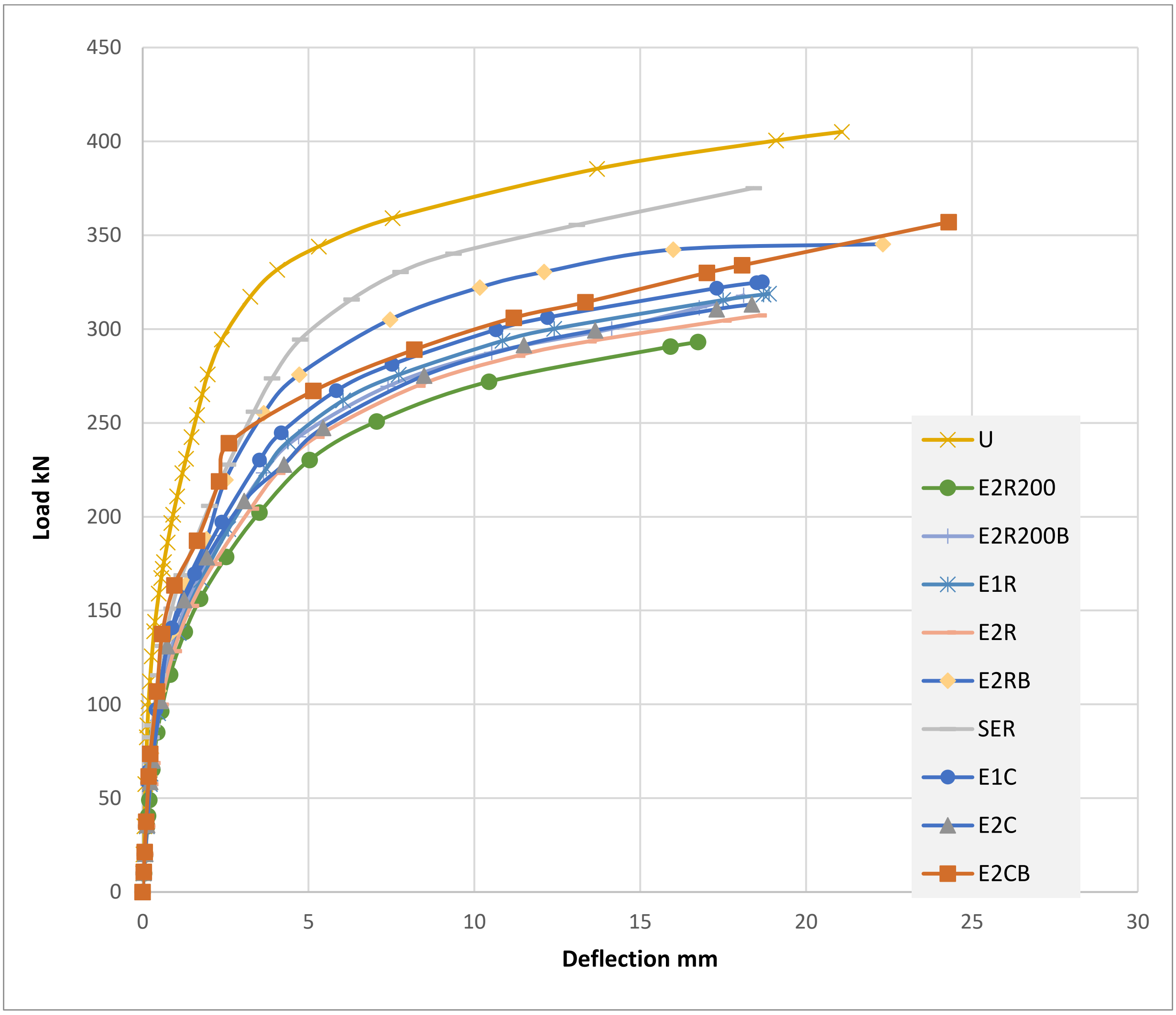


Fig. 6 Load-deflection curves

Waffle slab stiffness

The stiffness of the waffle slabs was recorded at the service load level (0.65 Pu)[12]. From the values listed in Fig.7, The solid waffle stiffness reveals a unique stiffens (162.2 kN/mm). While the opening slabs decreased by (42.6~60.8 %). With better behavior under BTRM strengthening.

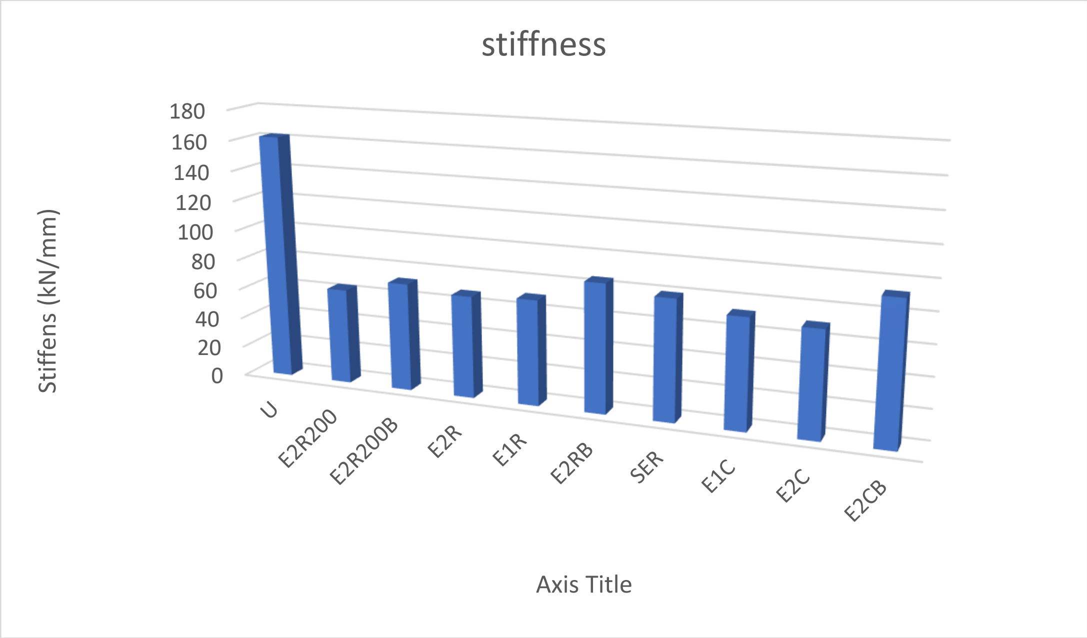


Fig. 7 Stiffness of waffle slabs

Ductility ratio

The ductility ratio was calculated from division of max deflection over deflection at service load level as shown in Fig.8. Solid slab was the highest ductility value. BTRM technique reveals a significant improvement on waffle slab stiffness.

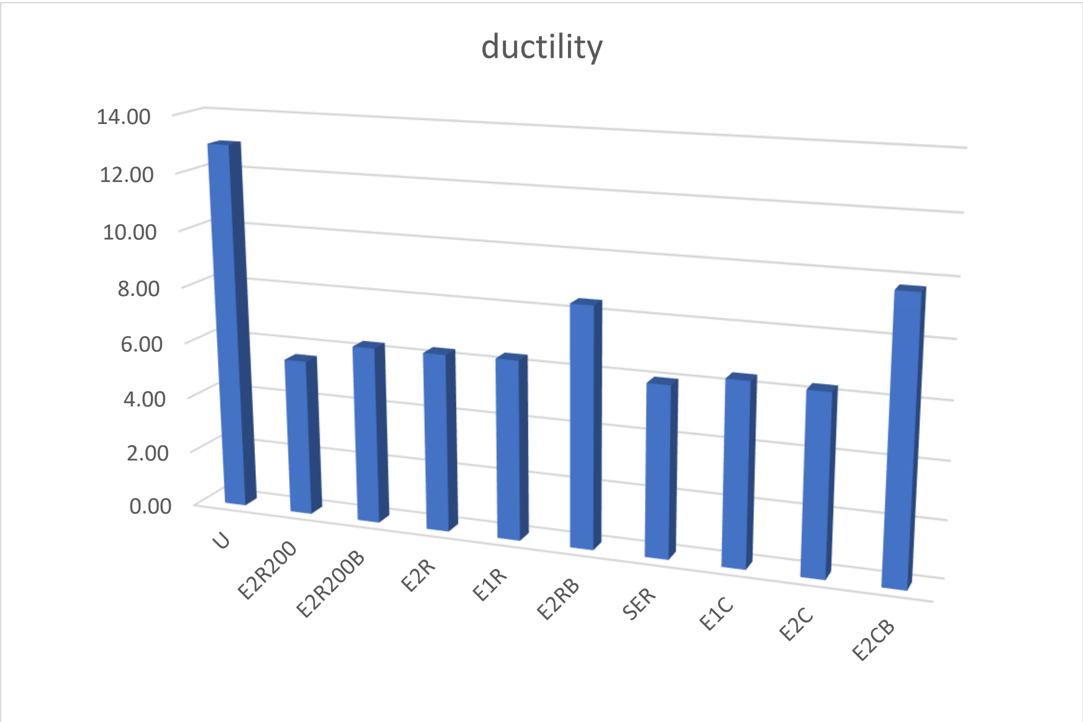


Fig. 8 Ductilty ratio

Toughness results

Slab E2CB shows a spectacular result that almost same stiffness as solid slab, while cutting ribs by large opening in slab E2R200 led to a deterioration in waffle slab energy absorption by 46.4%. Although it’s raised when slab E2R200B was strengthen using BTRM by 17.3%.as shown in Fig.9.

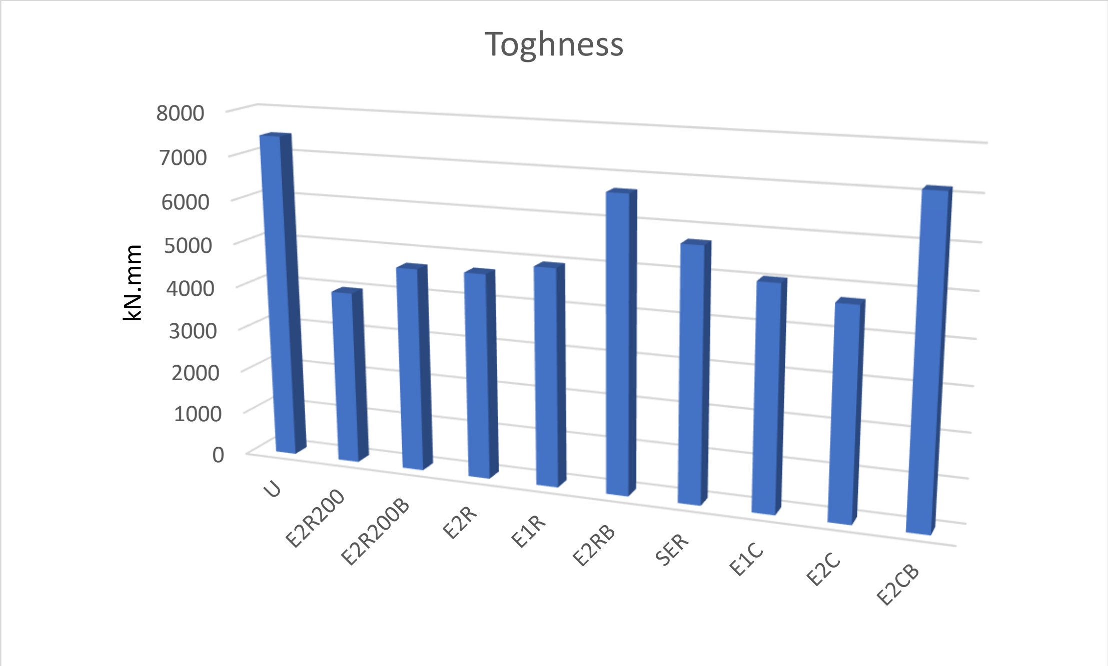


Fig. 9 Toughness of waffle slabs

5. **Conclusions**

- In comparison to the catted opening of the second rib intersection (E2 type), the opening located in the first rib intersection (E1 type) exhibited stiffer behaviour.

- The position of the opening appears to be a highly effective parameter for the loading capacity of the tested specimens.

- The BTRM method of warping the catted ribs significantly enhanced ductility, stiffness, energy absorption and flexural strength. The BTRM technique had a marked impact on waffle slab strengthening and improved structural behaviour, with no evidence of matrix debonding observed.

- At the same geometric conditions, a large opening (200 mm) results in a noticeable drop in stiffness and loading capacity compared to a smaller opening (150 mm).

- Despite being the closest opening to the slab centre, the hole surrounded by ribs, as in the (SER) slab, exhibits a higher loading capacity and stiffness.

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