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Electro-welded lattice reinforcement in reinforced concrete ribbed slabs

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Research Paper

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Electro-welded lattice reinforcement in reinforced concrete ribbed slabs

Shear strength of precast concrete ribbed slabs reinforced with electro-welded lattice girders of variable height is experimentally verified. Technical justification is given for the use of high latticework in the reinforcement of precast lightweight double-tee ribbed slabs and precast reinforced concrete slabs 30 cm in thickness. It was established that the contribution of concrete to shear strength was always higher than the expected values according to Spanish standards. Furthermore, as low lattice ribbed slabs exhibited lower ultimate shear strength values than the ones expected based on the standards, the need arose to provide an adequate height of lattices in ribbed slabs to ensure anchorage of the compressed area in order to develop the strut-and-tie mechanisms. Consequently, lattice girders with approximately 80% of specimen height are highly recommended in reinforced concrete ribbed slabs, when the length of lattice chords is 20 cm.

Key words:

shear strength, lattice, basic electro-welded lattice, reinforced concrete, one-way slab

Prethodno priopćenje

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Električno zavarena armaturna rešetka u armiranobetonskim rebrastim pločama

U radu se provodi eksperimentalna provjera posmične čvrstoće montažnih betonskih rebrastih ploča različitih visina s električno zavarenom armaturnom rešetkom. Prikazano je tehničko obrazloženje korištenja visokih rešetki u armaturi montažnih lakih rebrastih ploča u obliku dvostrukog slova T i montažnih armiranobetonskih ploča debljine 30 cm. Utvrđeno je da je doprinos betona posmičnoj čvrstoći uvijek veći od vrijednosti koje se mogu očekivati prema španjolskim normama. Osim toga, kako se niske rešetkaste rebraste ploče odlikuju nižim vrijednostima granične posmične čvrstoće od onih koje se očekuju prema normama, utvrđeno je da se treba osigurati odgovarajuća visina rešetaka u rebrastim pločama kako bi se osiguralo sidrenje tlačne zone te razvoj mehanizama štapova i zatega. Zato se u armiranobetonskim rebrastim pločama svakako preporučuje korištenje rešetkastih nosača na otprilike 80 % visine uzorka kada dužina pojasa rešetke iznosi 20 cm.

Ključne riječi:

posmična čvrstoća, rešetka, osnovna električno zavarena rešetka, armirani beton, ploča nosiva u jednom smjeru

1. Introduction

Resistance of Reinforced Concrete (RC) components to shear force is a topic that has aroused great interest since the end of the nineteenth century [1]. Although the shear force transfer mechanisms are qualitatively well known, no agreement exists on the quantification of shear resistance in reinforced concrete [2]. In qualitative terms, the majority of researchers and most RC dimensioning specifications in building codes affirm that shear resistance of concrete beams is a combination of the contribution of the concrete and, if present, of its transverse reinforcement [2].

The contribution of concrete takes into account tangential tensile stresses transferred within the compressed zone of the component, shear transfer problem, aggregate packing, and lateral load transfer. Its value principally depends on the quantity of longitudinal reinforcement, concrete strength, maximum aggregate size, and shear span. Its evaluation is based on empirical methods [3]. However, the contribution of transverse reinforcement can be calculated with rational models, such as the lattice analogy proposed by Ritter [4] and Mörsch [5].

Recent investigations have resulted in the development of numerical models that are capable of estimating strength mechanisms under tangential forces and, particularly, shear forces occurring in RC structures, although the formulas for manual calculation of shear stress forces still entail a large empirical content. These highly non-linear forces are characterized by a strong multi-axial tensile deformation mechanism [6-12] that produces oblique cracking non-parallel to the plane of the main section.

The shear strength capacity of a concrete specimen also depends on other factors that are independent of transverse section. These factors are the position of load imposed on the beam [13], the existence or absence of inflection points (points of curvature change), and the type of loading that is applied. The great majority of existing investigations use a beam model on simple supports that is subjected to two symmetric point loads [14].

At present, it is common practice to employ basic electro-welded lattice girder reinforcement within the ribs of half-slabs and lightweight precast slabs [15]. This lattice reinforcement meets two distinct basic functions: during the construction phase, it is an element that adds rigidity to the lower concrete slab, due to the upper longitudinal bars; and in the structural phase, it functions as reinforcement whose role is to withstand horizontal, tensile and, fundamentally, shear stress forces [16, 17].

In the industrial manufacturing process of the basic electro-welded lattice rod reinforcement, the spacing or chords between the lattice-forming rods are always fixed at 20 cm, their height varying up to a maximum of 30 cm. This height limit of the lattice (30 cm) means that in units higher than 36 cm, proper anchorage of the lattice cannot be guaranteed in the compressed section of the specimen, preventing development of strut-and-tie mechanisms. In contrast, the following is specified in Article 44.2.3.4.1 of the Spanish RC standard with regard to the longitudinal distance between transverse reinforcement, s_t [18]:

$$s_t \leq 0{,}75 \cdot d \cdot (1 + \cot\alpha) \leq 600 \text{ mm if } V_{rd} \leq 1/5 \cdot V_{u1} \tag{1}$$

$$s_t \leq 0{,}60 \cdot d \cdot (1 + \cot\alpha) \leq 450 \text{ mm if } 1/5\ V_{u1} < V_{rd} \leq 2/3 \cdot V_{u1} \tag{2}$$

$$s_t \leq 0{,}35 \cdot d \cdot (1 + \cot\alpha) \leq 300 \text{ mm ih } V_{rd} > 2/3 \cdot V_{u1} \tag{3}$$

where

V_{rd} - design value of the effective shear stress
V_{u1} - ultimate shear force failure due to diagonal compression in the web
D - effective depth of cross-section with reference to the longitudinal bending reinforcement
α - angle of reinforcement to the member's axis

Therefore, given that the spacing is invariable at 20 cm, and depending on the height of the piece, the requirement regarding the maximum longitudinal separation between transverse reinforcement may not be met if the shear value is high, i.e. if $V_{rd} < 2/3 \cdot V_{u1}$, because it must verify that it is lower than 300 mm, but also the additional condition.

This study is partly a consequence of the concerns, in relation to ultimate shear, of one part of the precast concrete sector, which produces structural components that incorporate this type of reinforcing latticework. Some of them employ high lattices to ensure adequate anchorage of the compressed section and proper development of the strut-and-tie mechanism, while others try to reduce the price of their products by reducing the height of lattice girders and, hence, by lowering the quantity of reinforcement in the elements. Therefore, the objective of the study is to experimentally check the shear strength capacity of an RC ribbed slab with electro-welded lattices of different heights.

The aim is thus to present technical justification about the use of a high lattice, within set limits, in the reinforcement of any rib of a lightweight double-tee slab or a precast RC slab because simple introduction of a lattice does not mean that the strut-and-tie mechanisms will be developed. The lattice must have an adequate height to reach the compressed zone so as to ensure a correct anchorage of this area.

2. Methodology and materials

2.1. Methodology

The study comprises three series of tests, each of which with the following objectives.

In Series 1, a beam with a span of 1.20 m and lattice girder reinforced ribs of 15, 19, and 24 cm in height, will be tested (Figure 1). The objective is to determine contribution of the lattice, as a function of its height, to the shear strength. The 15 cm high latticework is not anchored to the compressed concrete area, unlike the 24 cm high lattice, where the anchorage is guaranteed. The 19 cm high lattice is half way between both ends.

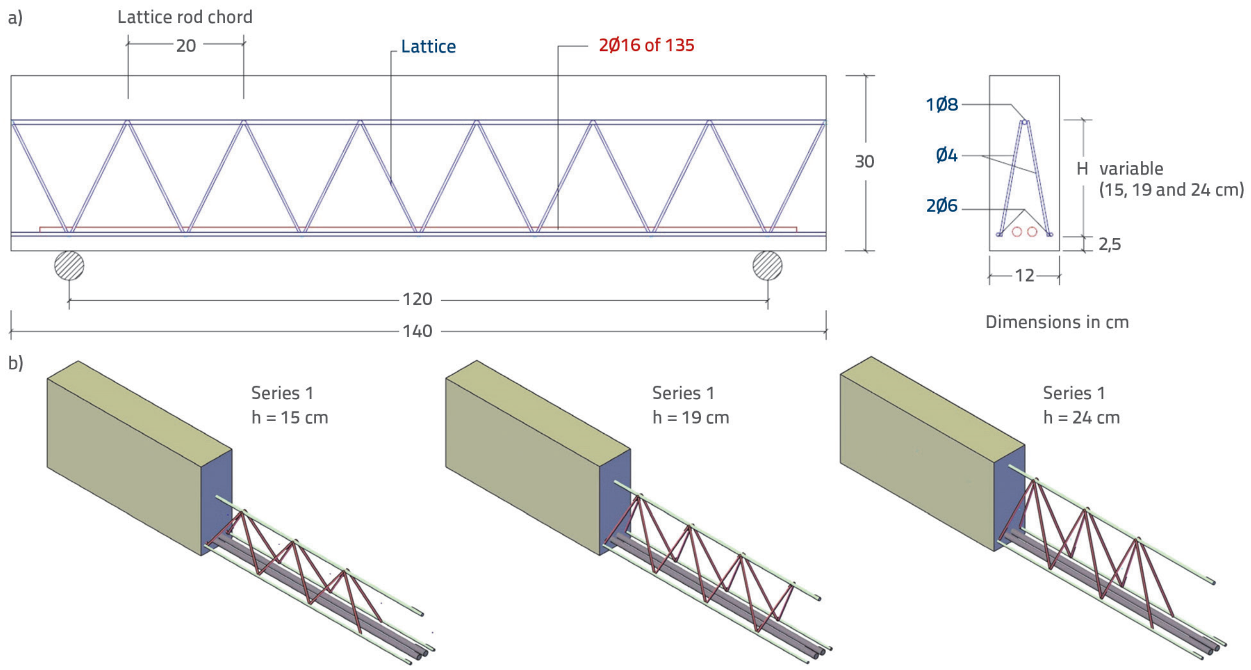

Figure 1. Series 1 specimens: a) Longitudinal and transverse sections, b) 3D view of 3 types of specimens tested. From left to right, with lattice of 15, 19, and 24 cm

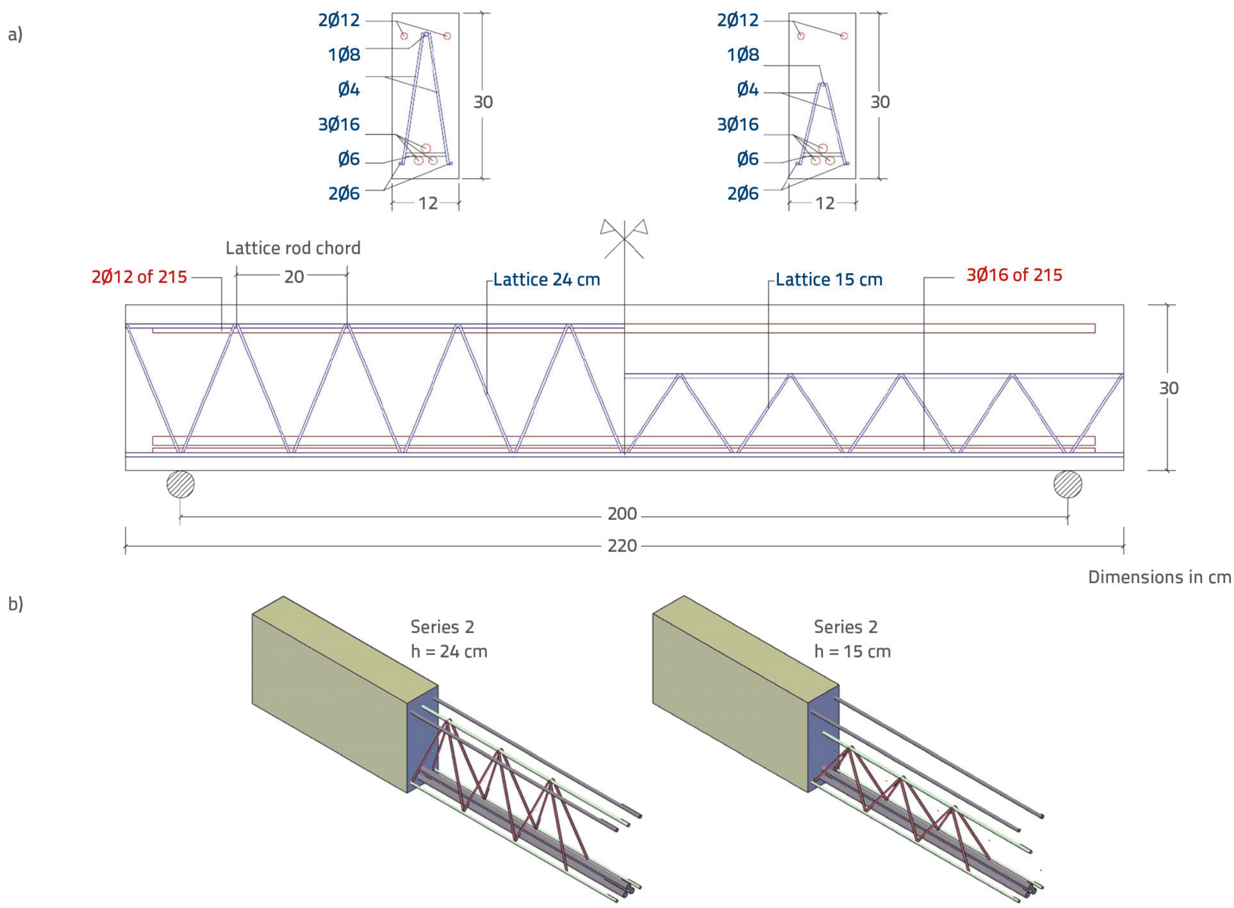

Figure 2. Series 2 models: a) Transverse and longitudinal sections, b) 3D view of 2 types of specimens tested. From left to right, with 24 cm lattice and with 15 cm lattice

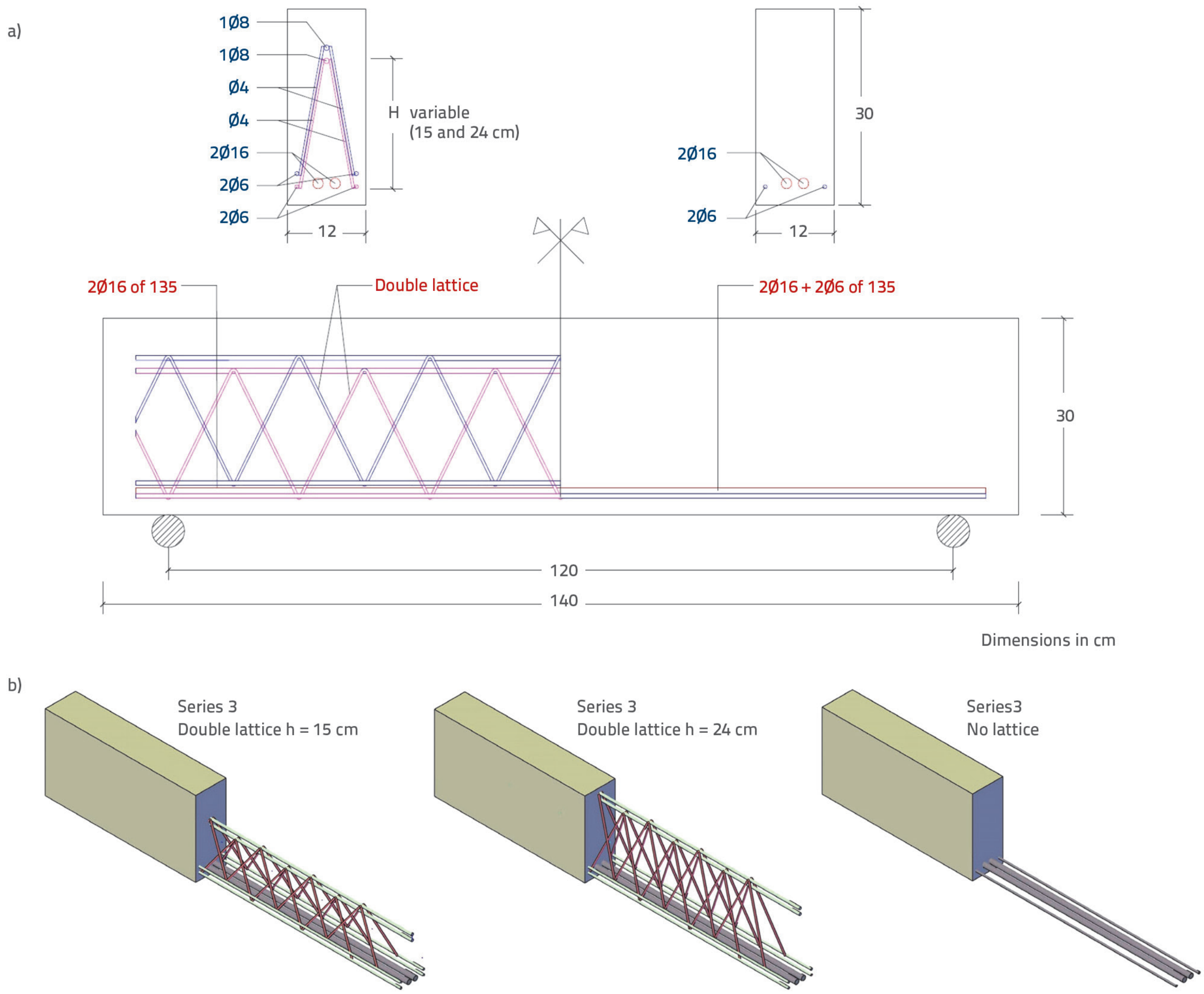

Figure 3. Models of Series 3, a) Transverse and longitudinal sections, b) 3D view of 3 types of specimens tested. From left to right: double lattice 24 cm in height, double lattice 15 cm in height, and no lattice

In Series 2, the behaviour of a beam with a span of 2.00 m and lattice girder reinforced ribs of 15 and 24 cm in height will be analysed (Figure 2).

The aim is to study the relation between the distance from the point of load application to the support and the thickness of the test specimen. The distance from the load application to the support in Series 1 is equivalent to 2.2 times the effective depth of the test specimen, while it is 3.7 times in Series 2. Spanish standard on precast one-way slabs (EFHE) [19], no longer in force, recommended a distance of 3.5 times the height, for the shear test on ribbed slabs. Due to longer distance between the point of load application and the support, the beam is reinforced with two additional bars (2Φ16) in the upper part (in the compressed area).

Therefore, the aim is to verify behaviour of ribbed slabs under shear forces, increasing the distance from the point of load application to supports, and confirming whether that distance has any influence on the ultimate shear strength of the test specimen. Finally, a beam with a span of 1.20 m and ribs with no transverse reinforcement and ribs reinforced with double-lattice girders 15 and 24 cm in height, will be studied in Series 3 (Figure 3). The same assumptions are retained, except with regard to the quantity of transverse reinforcement, given that EHE-08 [18] under article 44.2.3.4.1 permits the use of latticework to absorb shear stress, with no need for the ribs to have vertical lattice reinforcement under 40 cm in height.

In Series 3, test specimens with no shear reinforcement are opposed to specimens with twice the usual amount of transverse staggered reinforcement. The influence of the amount of reinforcement and the separation of the transverse reinforcement on shear force strength is examined, in order to confirm contribution of concrete in a test specimen with no transverse reinforcement, and failure of a test specimen with higher quantity of transverse reinforcement.

Six Series 1 specimens were constructed to conduct this analysis, 2 with each type of lattice girder, of rectangular section, 12 cm in width by 30 cm in height (Figure 1). The objective was to simulate ribs of lightweight double-tee slabs. Although it is true that a real ribbed half slab assumes a double T form, for the purposes of determining its strength capacity under shear

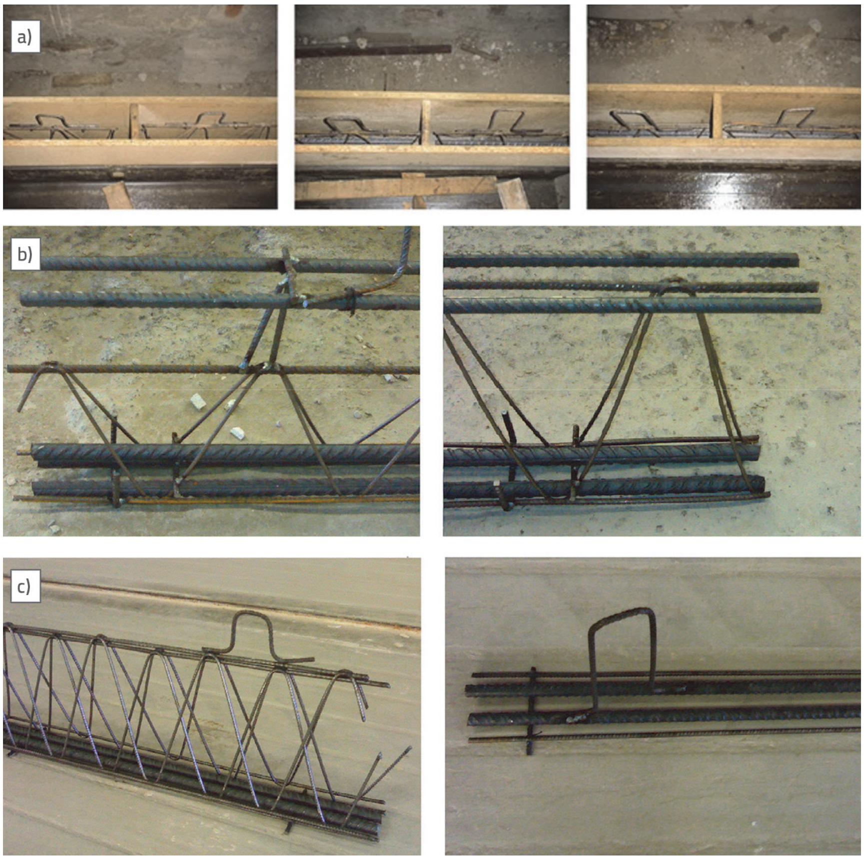

Figure 4. Photos of reinforcement before concreting: a) Longitudinal layout of the Series 1 latticework at heights of 24, 19, and 15 cm, from left to right; b) Reinforcement in Series 2, from left to right, lattice of 15 cm and 24 cm, c) Reinforcement in Series 3, from left to right: 24 cm-height double lattice reinforcement and reinforcement in specimen without lattice

stress, the flanges of the double-tee contribute no added value against shear strength. The layout of longitudinal reinforcement (Figure 1) was the same in all cases, ensuring that a tie of the lattice girder coincided with the support points in the test.

The latticework at its respective heights of 24, 19, and 15 cm, can be seen from left to right in Figure 4a. Special care was taken over its layout, so as to analyse the form of the breakage in relation to the layout of the sloped reinforcement of the lattice.

Four Series 2 specimens were prepared with a calculated span of 200 cm, unlike the 120 cm span employed in Series 1. Longitudinal reinforcement needed to avoid flexural failure was increased (Figure 2). Two models were reinforced with lattice girders 24 cm in height and the other two with lattice girders 15 cm in height. The transverse section in use was the same as for Series 1, with a width of 12 cm and a height of 30 cm. Figure 4b shows reinforcement before concreting.

Finally, four Series 3 models were prepared, to conclude the study, each having a calculated span of 120 cm, two of them with a double lattice, and another two without transverse reinforcement (Figure 3). In the double lattice models, staggered reinforcement was laid out, thereby reducing the chord of the lattice rod to 10 cm. Figure 4c shows the lattice reinforcement of Series 3 before concreting.

2.2. Materials

The following types of steel reinforcement were used:

- B 500 SD steel in longitudinal reinforcement, 16 mm in diameter
- B 500 T steel in longitudinal bars of the basic reinforcement, 6 and 8 mm in diameter

Table 1. Tensile strength of steel bars [MPa]

Specimen	Ø 16 mm		Ø 8 mm		Ø 6 mm		Ø 4 mm	
	f_y [MPa]	f_s [MPa]	f_y [MPa]	f_s [MPa]	f_y [MPa]	f_s [MPa]	f_y [MPa]	f_s [MPa]
Specimen 1	515.8	669.8	498.8	648.2	645.1	708.4	752.1	784.0
Specimen 2	522.3	675.4	498.0	650.7	633.1	699.2	762.2	791.2
Specimen 3	514.7	652.1	508.3	659.3	670.9	693.9	782.3	827.0
Average value	517.6	665.8	501.7	652.7	649.7	700.5	765.6	800.7

Table 2. Uniaxial compressive strength [MPa]

Specimen	Series 1	Series 2	Series 3
Specimen 1	24.7	23.4	19.0
Specimen 2	24.3	22.6	21.7
Specimen 3	27.1	22.8	22.7
Specimen 4	28.3	23.8	22.5
Average value [MPa]	26.1	23.2	21.5

- B 500 T steel in smooth diagonal bars of the lattice, 4 mm in diameter

These different bars were subjected to tensile tests, and the corresponding results are given in Table 1. Concrete mix contained I 52,5 R cement, 0-6 mm fine aggregate, and 6-12 mm coarse aggregate. Its characteristic strength under compression was determined at the time of completing each test, through the tests of a series of specimens obtained from the mix and cured under the same conditions as the concrete test specimen, both after 28 days. The results obtained on cylindrical specimens are presented in Table 2.

3. Theoretical values of the model and expected values

This section presents values that were obtained using the theoretical model included in Spanish specifications for reinforced concrete EHE-08 [18], with theoretical values of the characteristics of the materials (theoretical model) and, on the other hand, with real tensile strength values of steel bars obtained in the tests, defined as expected values, as shown in Table 1.
The model employed was a beam 140/220 cm in length, with supports placed at 10 cm from the ends of the test specimen, so that a calculated span amounts to 120 / 200 cm. The loading arrangement was a point load applied at mid-span, i.e. at the centre of the test specimen (Figure 5). The calculated span of 120 cm was used in Series 1 and 3, while the calculated span of 200 cm was used for Series 2.

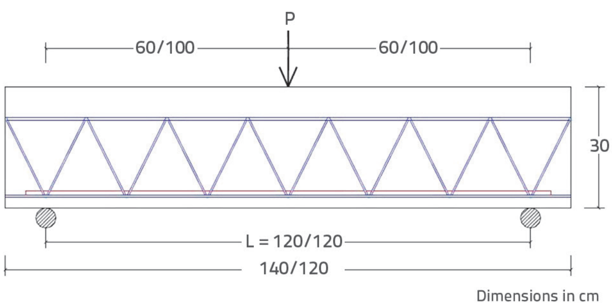

Figure 5. Test model

When applying point load at mid-span of a model resting on two supports, the maximum flexural force (located at the mid-span) can be calculated with Eq. (1), while Eq. (2) can be used for calculating maximum shear forces (on both supports):

$$M_f^+ = \frac{P \cdot L}{4} \tag{1}$$

$$V = \frac{P}{2} \tag{2}$$

where, M_f^+ is the maximum flexural moment at mid span; P is the applied load; L is the distance between supports; and V is the maximum shear obtained on the supports. The weight of the test specimen was ignored as its influence on force values is negligible.

The test set up consisted of a galley equipped with a 500 kN MTS actuator, with a load cell to measure the applied force and an internal LVDT for displacement control. In addition, height-regulated trestle supports and tools, especially designed for these tests by the research team, were used for the application and distribution of load (Figure 6).

Figure 6. Test set up

The MTS equipment was controlled using the Basic TestWare software with which both force and displacement can be controlled, as well as the data acquisition over time. The tests were conducted by controlling the actuator displacement at a constant speed of 0.01 mm/s. The test equipment was fitted with a data acquisition card, which recorded the time during which the actuator was applying the force, as well as piston displacement.
Given that the test specimen was a section of reinforced concrete, the specifications of EHE-08 [18] were applied for the determination of shear fatigue under tension in the web of the test specimen, V_{u2}, according to Eq. (3) for specimens with no shear reinforcement (and without axial forces) and Eq. (4) for specimens with shear reinforcement.

$$V_{U2} = V_{cu} = \left(\frac{0,18}{\gamma_c} \cdot \xi \cdot \left(100 \cdot \rho_1 \cdot f_{cv}\right)^{1/3} \right) \cdot b_o \cdot d \tag{3}$$

$$V_{U2} = V_{cu} + V_{su} = \left(\frac{0,15}{\gamma_c} \cdot \xi \cdot \left(100 \cdot \rho_1 \cdot f_{cv}\right)^{1/3} \right) \cdot \beta \cdot b_o \cdot d + z \cdot \sin\alpha \left(\cot\alpha + \cot\theta\right) \cdot \sum A_\alpha \cdot f_{y\alpha,d} \tag{4}$$

where
V_{u2} - ultimate shear force failure due to tensile force in the web (kN)
V_{cu} - contribution of concrete to shear strength
V_{su} - contribution of the web's transverse reinforcement to shear strength
γ_c - partial safety coefficient of concrete
ξ - defined according to Eq. (5).

$$\xi = \left(1 + \sqrt{200/d}\right) \leq 2.0 \tag{5}$$

where

d - effective depth of cross-section with reference to the longitudinal bending reinforcement (mm)

ρ_l - geometric ratio of the main longitudinal tensioning reinforcement, whether bonded passive or active reinforcement, anchored at least a distance, d, away from the section considered, defined by Eq. (6)

$$\rho_1 = \frac{A_s}{b_0 \cdot d} \leq 0.02 \tag{6}$$

where

f_{cv} - effective shear strength of concrete (N/mm²), with a value of $f_{cv} = f_{ck}$, with f_{ck} being the concrete compression strength which, for the purpose of these equations, shall be considered not to exceed 60 N/mm². In the case of reduced concrete control, f_{cv} cannot be greater than 15 N/mm²

b_o - net minimum width of the test specimen (mm)

z - mechanical lever arm. In pure bending and in the absence of more accurate calculations, an approximate value can be calculated by Eq. (7):

$$z = 0{,}9 \cdot d \tag{7}$$

where

α - angle of reinforcement to the specimen axis

A_s - area of passive reinforcement (mm²)

A_α - area per unit length of each set of reinforcement forming an angle α with the main axis of the specimen

$f_{y\alpha,d}$ - design yield strength of reinforcement $A\alpha$.

Θ - angle between the concrete compression struts and specimen axis. Its values must satisfy Eq. (8):

$$0.5 \leq \cot\theta \leq 2.0 \tag{8}$$

where

β - is a parameter defined by Eqs. (9) and (10):

$$\beta = \frac{2 \cdot \cot\theta - 1}{2 \cdot \cot\theta_e - 1} \quad \text{if } 0.5 \leq \cot\theta \leq \cot\theta_e \tag{9}$$

$$\beta = \frac{\cot\theta - 2}{\cot\theta_e - 2} \quad \text{if } \cot\theta_e \leq \cot\theta \leq 2.0 \tag{10}$$

θ_e - reference angle of the inclination of cracks.

In addition, a minimum value is established, as shown in Eq. (11)

$$V_{U2} = \left(\frac{0{,}075}{\gamma_c} \cdot \xi^{3/2} \cdot f_{cv}^{\ 1/2}\right) \cdot b_o \cdot d \tag{11}$$

Confirmation of the shear strength due to diagonal compression in the web, V_{u1}, is not detailed, as $V_{u1} > V_d$ holds true for all test specimens, where V_d is the design shear strength.

These equations, Eqs. (3) and (4), are identical to the ones given in Eurocode-2 [20], the European Standard for concrete elements, i.e. for calculating shear strength for these elements. Theoretical shear strength values of concrete ribs were therefore calculated for each specimen of the series so that they could be compared with test results. The theoretical analysis was applied to the section on the trestle supports, because it is in that section that the highest calculated shear value, V_d, is found, due to test layout.

Characteristics of materials for theoretical analysis were:

HA-25 Concrete: f_{ck} = 25 N/mm²

B 500 SD Steel: f_{yk} = 500 N/mm² (longitudinal flexural reinforcement)

B 500 T Steel: f_{ys} = 550 N/mm² (shear reinforcement in lattice girders)

The values of the variables introduced in Eqs. (3) and (4) are shown in Table 3. The obtained shear values are shown below

Table 3. Values for calculation of V_{u2} with and without shear reinforcement

Lattice height / Variable	Series 1			Series 2		Series 3		
	15 cm	19 cm	24 cm	15 cm	24 cm	15 cm	24 cm	No lattice
γ_c	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
ξ	1.864	1.864	1.864	1.876	1.876	1.867	1.867	1.864
ρ_1	0.0143	0.0143	0.0143	0.0211	0.0211	0.0161	0.0161	0.0143
f_{ck} [MPa]	25	25	25	25	25	25	25	25
b_o [mm]	120	120	120	120	120	120	120	120
d [mm]	267.62	267.62	267.62	260.72	260.72	266.34	266.34	267.62
α [°]	56.310	62.241	67.380	56.310	67.380	56.310	67.380	
$A\alpha$ [mm²/mm]	0.126	0.126	0.126	0.126	0.126	0.251	0.251	
$f_{y\alpha,d}$	400	400	400	400	400	400	400	400
θ [°]	45	45	45	45	45	45	45	45
θ_e [°]	45	45	45	45	45	45	45	45
β	1	1	1	1	1	1	1	1

Table 4. Theoretical shear strength values (kN)

Variable \ Lattice height	Series 1			Series 2		Series 3		
	15 cm	19 cm	24 cm	15 cm	24 cm	15 cm	24 cm	No lattice
V_{cu} (kN)	19.72	19.72	19.72	22.01	22.01	20.45	20.45	23.66
V_{su} (kN)	16.79	16.35	15.83	16.36	15.42	33.42	31.51	
V_{u2} (kN)	36.51	36.07	35.55	38.36	37.43	53.87	51.97	23.66

Table 5. Expected values in shear strength tests with tensile strength values of Table 1 (kN)

Variable \ Lattice height	Series 1			Series 2		Series 3		
	15 cm	19 cm	24 cm	15 cm	24 cm	15 cm	24 cm	No lattice
EV_{cu} (kN)	19.72	19.72	19.72	22.01	22.01	20.45	20.45	23.66
EV_{su} (kN)	32.13	31.30	30.30	31.31	29.52	63.96	60.32	
EV_{u2} (kN)	51.85	51.01	50.02	53.31	51.53	84.42	80.77	23.66

in Table 4. Additionally, apart from values given in Table 4, which refer to characteristics of the materials for theoretical analysis, the expected values on real characteristics of the materials used in the tests were also calculated. Therefore, taking into account tensile test values obtained for the bars inserted in specimens (shown in Table 1), the expected theoretical shear-force values were also calculated, i.e. the shear force that the test specimens will have to withstand according to the real tensile strength of the bars (Table 5). These expected values were calculated because the real tensile strength can be higher than the ones included in theoretical models and, hence, those real values can bias the results. More accurate shear strength values can be obtained if real values on characteristics of materials are known. The expected values for V_{cu}, V_{su}, and V_{u2} are denominated as EV_{cu}, EV_{su}, and EV_{u2}, respectively.

The increased value of V_{su} in relation with the calculated theoretical value was due to the higher strength of lattice rods. Their tensile strength in the tests was 765.6 MPa.

Finally, as commented before, dead loads of the specimens were not included in the calculations because their values (1.26 kN, 1.98 kN, and 1.26 kN for Series 1, 2, and 3, respectively) can be neglected when compared to expected values shown in Table 5.

4. Results and discussion

Actuator displacement was controlled during the tests, at a constant velocity of 0.01 mm/sec. The actuator was equipped with a data acquisition card, where the time of the force applied by the actuator and piston displacement were measured. Test results and loading times were recorded for each test, as shown in Figure 7. With a constant velocity of 0.01 mm/sec, an interval of 200 seconds equals to a displacement of 2 mm.

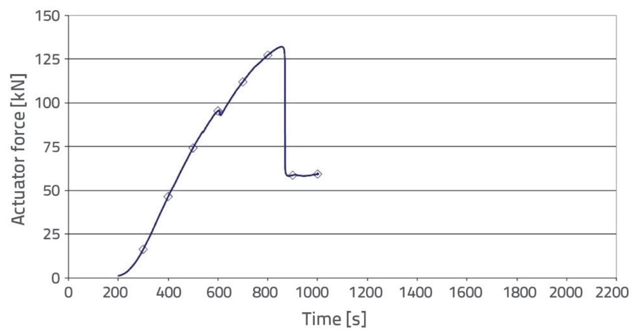

Figure 7. Model graph of test results for the force-time diagram

4.1. Series 1

The general pattern of all graphs involved a peak corresponding to the shear cracking that propagated from one face of the test specimen to the other, and then the load fell abruptly as the lattice reinforcement rods were broken. It should be mentioned that this was preceded by micro-fissuring. According to Eq. (2), the maximum shear value was calculated as a half of the applied load.

Results of all six tests are shown in Figure 8a in order to enable their comparison over time. The results are staggered at (+200 sec.) intervals to avoid overlapping. As previously stated, an interval of 200 seconds means a displacement of 2 mm in the test. Additionally, Figure 8b shows the force-displacement diagram of all the specimens of Series 1. As the displacement speed is constant (0.01 mm/s), the shape of both diagrams is similar.

It can be seen that the first peak corresponded to the failure of concrete which occurred at around 75 and 100 kN (except for the specimen 1 with a 24 cm-high lattice), while the maximum load was over 100 kN in all the cases, with an average value of around 125 kN. The behaviour of the three models was very similar, regardless of the height of the latticework.

Table 6. Shear strength test results (in kN)

Variables	Lattice 15 cm (1)	Lattice 15 cm (2)	Lattice 19 cm (1)	Lattice 19 cm (2)	Lattice 24 cm (1)	Lattice 24 cm (2)
Concrete cracking (TV_{cu}) [kN]	44.1	41.8	44.8	39.3	34.3	44.8
Expected V_{cu} (EV_{cu}) [kN]	19.72	19.72	19.72	19.72	19.72	19.72
Ratio TV_{cu} / EV_{cu}	2.24	2.12	2.27	1.99	1.74	2.27
Ultimate shear strength (TV_{u2}) [kN]	53.12	66.00	56.92	60.44	61.84	70.56
Expected V_{u2} (EV_{u2}) [kN]	51.85	51.85	51.01	51.01	50.02	50.02
Ratio TV_{u2} / EV_{u2}	1.02	1.27	1.12	1.18	1.24	1.41

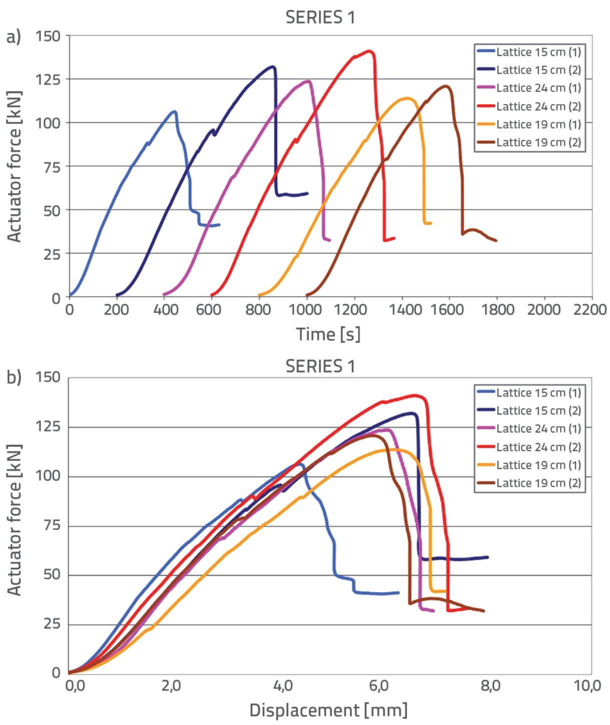

Figure 8. Test results for Series 1, a) Force-time diagram (staggered at 200 second intervals), b) Force-displacement diagram

The form of shear failure was also analysed in the three different models reinforced with lattice reinforcement measuring 15, 19, and 24 cm in height, respectively (Figure 9). The maximum load of tests in the first specimen with the lattice of 15 cm, and the second one with the lattice of 24 cm, was slightly higher as each crack propagated through 2 planes of latticework, whereas the crack in test 1 of the 19 cm-high lattice only ran through one lattice plane. A second shear crack, separated at approximately the same distance as the lattice rods, 20 cm, may be seen in the test involving the second specimen with the 24 cm-high lattice girder.

The exact numerical results of the tests are given in Table 6. The test results obtained for V_{cu}, V_{su}, and V_{u2} are denominated as TV_{cu}, TV_{su}, and TV_{u2}, respectively.

Table 6 shows that test values for the contribution of concrete to shear strength (TV_{cu}) are twice higher than the expected values (EV_{cu}), except for the specimen 1 with the lattice 24 cm in height. However, as to the ultimate shear force failure, while the values for specimens with low lattice (15 cm) were expected to be higher than those for other configurations (EV_{u2}), the obtained values (TV_{u2}) were the lowest (on average): 53.12 and 66.00 kN. On the contrary, although specimens with high lattice (24 cm) were supposed to obtain lower V_{u2}, they obtained the highest average values (61.84 and 70.56 kN). Therefore, these results show that the lattice in ribbed slabs must arrive to the upper part of the element to ensure a correct anchorage of the compressed area. However, the values obtained in the test for the low lattice ribbed slabs are greater than the expected values (the ratio is in excess of 1 in both cases), but the greatest ratio is obtained for high lattice ribbed slabs. As it could be expected, the values for intermediate height lattices are between the two results.

4.2. Series 2

The results for four tests are shown in Figure 10a where, once again, they are staggered at 200 second intervals, so that there is no overlap of the graph curves. Figure 10b shows the force-displacement diagram for specimens in Series 2. The exact values of the tests are presented in Table 7.

Figure 9. Shear failure cracking of Series 1 samples, with 15, 19, and 24 cm lattice reinforcement, respectively

Table 7. Test results for shear strength [kN]

Variables	Lattice 15 cm (1)	Lattice 15 cm (2)	Lattice 24 cm (1)	Lattice 24 cm (2)
Concrete cracking (TV_{cu}) [kN]	38.285	43	35.794	50.99
Expected V_{cu} (EV_{cu}) [kN]	22.01	22.01	22.01	22.01
Ratio TV_{cu} / EV_{cu}	1.74	1.95	1.63	2.32
Ultimate shear strength (TV_{u2}) [kN]	42.03	45.97	54.93	61.68
Expected V_{u2} (EV_{u2}) [kN]	53.31	53.31	51.53	51.53
Ratio TV_{u2} / EV_{u2}	0.79	0.86	1.07	1.20

Table 8. Test results for shear strength values

Variables	No lattice (1)	No lattice (2)	Double lattice 15 cm	Double lattice 24 cm
Concrete cracking (TV_{cu}) [kN]	34.72	37.22	57.76	65.81
Expected V_{cu} (EV_{cu}) [kN]	23.66	23.66	20.45	20.45
Ratio TV_{cu} / EV_{cu}	1.47	1.57	2.82	3.22
Ultimate shear strength (TV_{u2}) [kN]	35.87	39.25	73.85	85.03
Expected V_{u2} (EV_{u2}) [kN]	23.66	23.66	84.42	80.77
Ratio TV_{u2} / EV_{u2}	1.52	1.66	0.87	1.05

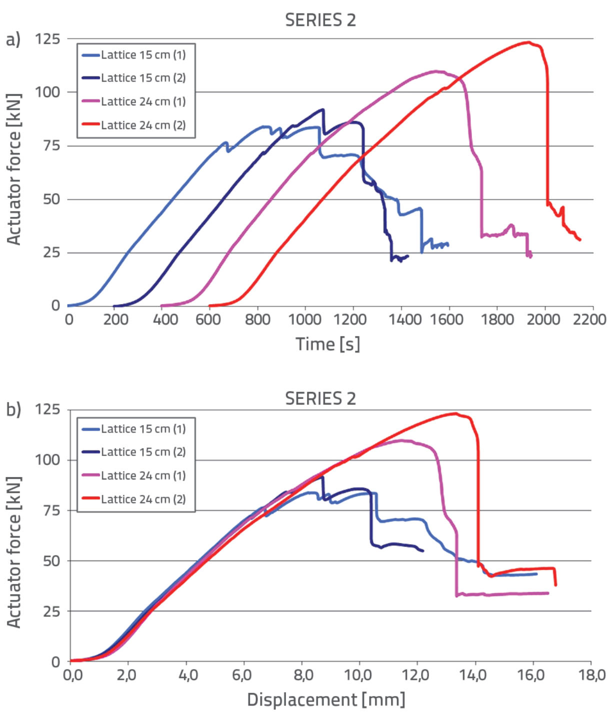

Figure 10. Test results for Series 2: a) force-time diagram (staggered at 200 second intervals), b) force-displacement diagram

The cracks detected in concrete specimens were obtained at compressive forces of more than 70 kN in the four tests. As can be seen in Table 6, this corresponds to shear forces resisted by concrete beyond 35 kN and, in all the cases, values from the tests (TV_{cu}) obtained a ratio of more than 1.50 when compared to expected values (EV_{cu}). On the contrary, there is a greater difference between specimens with regard to ultimate shear forces. Whereas low lattice ribbed slabs obtained shear strengths (TV_{u2}) (42.03 and 45.97 kN) that are lower than expected (EV_{u2}), the results for high lattice ribbed slabs are above the expected value (ratio > 1.0). In this series, the aim was to verify the importance of an adequate height of the lattice in specimens when the ratio between the distance of the load and the support, and the effective depth of the specimen is over 3.5, as recommended in a Spanish standard on precast one-way slabs [19], which is no longer in force. As can be observed, in Series 2, when the ratio is 3.7 (compared to the ratio of 2.2 in Series 1), it points to the need of including high lattice girders in ribbed slab to provide for anchorage of the compressed zone. If the lattice is not high enough, real values are below the expected one, and hence, these configurations are not allowed.

4.3. Series 3

Figure 11a shows the results of the 4 tests of Series 3, with the same 200 second intervals as in the previous series. The force-displacement diagram is shown in Figure 11b. Table 8 shows the exact results obtained in the tests.

As it could be expected, in specimens with no shear reinforcement, the appearance of cracking signals that shear strength practically corresponds to the ultimate shear strength of concrete. In both specimens, the ratio between TV_{cu} and EV_{cu} was around 1.50, indicating that the real shear strength is higher than expected. Similarly, the ultimate shear strength for specimens with no lattice reinforcement is by 50 % higher compared to specifications given in EHE-08 [18] or in Eurocode 2 [20].

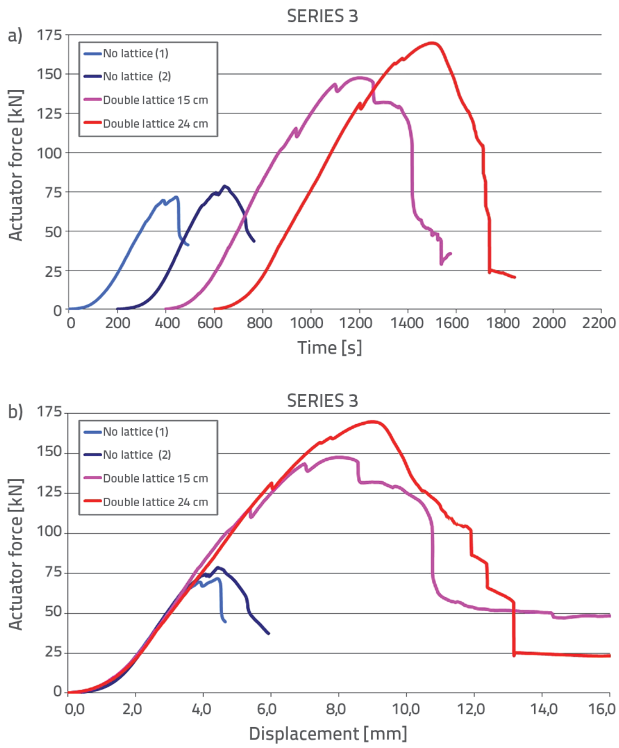

Figure 11. Test results for Series 3, a) force-time diagram (staggered at 200 second intervals), b) force-displacement

Nevertheless, the main interest of Series 3 is to show that an adequate height of the lattice must be ensured even with double lattice. In both specimens with double lattice (15 and 24 cm specimens), the shear strength of concrete obtained in the test (TV_{cu}) is by approximately three times higher than the one expected theoretically (EV_{cu}). The test specimens reinforced with double lattices consolidated the concrete better than single lattices and generated higher concrete shear resistance (V_{cu}) values. Nonetheless, once again, the ultimate shear strength of the low lattice ribbed slab in the test (TV_{u2}) is under the calculated value (EV_{u2}) which confirms that, even with double lattice, the lattice must have an adequate height to develop the strut-and-tie mechanism. In contrast, the ribbed slab with the 24 cm-high double lattice exhibited an ultimate shear strength (85.03 kN) higher than the value expected according to the standard (80.77 kN), thus implying correct anchorage of the compressed zone.

To sum up, it has been proven by means of these series of tests that, if electro-welded lattice reinforcement is placed in concrete ribbed slabs, they must have an adequate height to provide for development of the strut-and-tie mechanism. In specimens with a ratio between the distance from the point of the load application and the support, and the effective depth of the specimen of 2.2, a low lattice ribbed slab could still exhibit ultimate shear strength test values that are higher than the expected ones. Nonetheless, when the ratio was over 3.5, the value recommended in the Spanish standard for one-way ribbed slabs [19], the V_{u2} values in the test were below the expected ones. In contrast, in both situations, specimens with a 24 cm-high lattice obtained higher values in the test than in calculations. These results were also obtained when double lattices were introduced in the specimens. Consequently, the importance of an adequate height of lattices was confirmed.

5. Conclusions

After analysis of the results and behaviour of test specimens, the following conclusions were reached:

First of all, higher values than those resulting from the application of the current standard EHE-08 [18] were obtained with regard to the contribution of concrete to the ultimate shear strength, V_{cu}. Moreover, with double lattice, the specimens showed that they could better consolidate the concrete, and they generated a higher concrete shear resistance value (V_{cu}). Additionally, in all the tests, the final shear failure was preceded by cracking.

Nonetheless, the most important conclusions of this study are related to the contribution of the electro-welded lattice reinforcement to the ultimate shear strength. Higher shear strength can be obtained with higher quantity of transverse reinforcement. However, the lattice must have a proper height to develop the strut-and-tie mechanisms.

With a ratio of 2.2 for the distance between the point of application of the load and the support, and the effective depth of the specimen, low lattice (15 cm) ribbed slabs obtained ultimate shear strengths exceeding the calculated ones, but a higher ratio was obtained for specimens with higher lattices (19 and 24 cm). Nevertheless, when the above ratio was 3.7 (Series 2), low lattice ribbed slabs (15 cm) were not able to develop proper strut-and-tie mechanisms anticipated in the shear strength calculations, and lower values than those expected according to the standards were obtained. In contrast, high lattice specimens (24 cm) obtained TV_{u2} values that were by 14 % higher (on an average) than the expected one (EV_{u2}). This behaviour was also verified in specimens with double lattices. The low double lattices ribbed slab (15 cm) did not achieve the ultimate shear values expected according to the standards (the ratio TV_{u2}/EV_{u2} = 0.87), while the high double lattice specimens obtained a value that was by 5 % higher than expected.

Consequently, it has been demonstrated that electro-welded lattice reinforcement in reinforced concrete ribbed slabs must have an adequate height to guarantee the anchorage of the compressed area and, hence, develop the strut-and-tie mechanisms in order to withstand shear forces. It is highly recommended that the lattice girders have approximately 80 % of the height of the specimen, when the length of the lattice chords is 20 cm.

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