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Experimental investigation and numerical analysis of optimally designed composite beams with corrugated steel webs

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Abstract. Composite beams with corrugated steel webs represent a new innovative system which has emerged in the past decade for medium span in the construction technology. The use of composite beams with corrugated steel webs results in a range of benefits, including flexible spaces and reduced foundation costs in the construction technology. The thin corrugated web affords a significant weight reduction of these beams, compared with hot-rolled or welded ones. In the current research, an optimal designed I-girder beam with corrugated web has been proposed to improve the structural performance of continuous composite girder under bending moment. The experimental program has been conducted for six simply supported composite beams with different loading conditions. The tested specimens are designed by using one of the stochastic techniques called hunting search algorithm. In the optimization process, besides the thickness of concrete slab and studs, corrugated web properties are considered as design variables. The design constraints are respectively implemented from Eurocode 3, BS-8110 and DIN 18-800 Teil-1. The last part of the study focuses on performing a numerical study on composite beams by utilizing finite element analysis and the bending behavior of steel girders with corrugated webs experimentally and numerically verified the results. A nonlinear analysis was carried out using the finite element software ANSYS on the composite beams which were modelled using the elements ten-node high order quadrilateral type.

Keywords: composite structures; corrugated web beams; load carrying capacity; structural optimization; failure modes of beams; finite element analysis

1. Introduction

The use of long span steel beams results in a range of benefits, including flexible, free internal spaces and reduced foundation costs. Many large clear-span design solutions are also well adapted to simplify the integration of mechanical or utility services. Corrugated steel web beams provide economical solution and pleasing appearance for space structures. In construction applications, the web part of beam usually carries the compressive stress and transmits shear in the beam while the flanges support the applied external loads. By using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the load-carrying capability of the beam. In this case, the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability and deforms transversely. Corrugated web beams shown in Fig. 1 are built-up girders with a thin-walled, corrugated web and plate flanges.

Corrugated structure of the web cross-section not only increases the resistance of the beam against to shear force and other possible local effects, but also prevents the buckling due to loss of moment of inertia before the plastic limit. This specific structure of the web leads to a decrease in the beam unit weight and increase in the load carrying capacity. These efficient construction materials, commonly used in developed countries over years, can be utilized at the roofs as an alternative to space truss and roof truss, at the slabs as floor beams or columns under axial force. Although the designers are aware of the advantages of the composite systems to be produced with that beams, there is still not a detailed technical specification about their design and behavior. The first studies on the corrugated web beams were focused on the vertically trapezoidal corrugation.
Elgaaly *et al.* (1996, 1997) investigated the failure mechanisms of trapezoidal corrugation beams under loading conditions, namely shear mode and bending mode. They found that the web could be neglected in the beam bending design calculation due to its insignificant contribution to the beam's load-carrying capability. Besides that, the two distinct modes of failure under the effect of patch loading were dependent on the loading position and the corrugation parameters. These are found agreeable to the investigation by Johnson and Cafolla (1998) were further discussed in their writings. In addition, the experimental tests conducted by Li *et al.* (2000) demonstrated that the corrugated web beam has 2 times higher buckling resistance than the plane web type. According to Pasternak *et al.* (2010), the buckling

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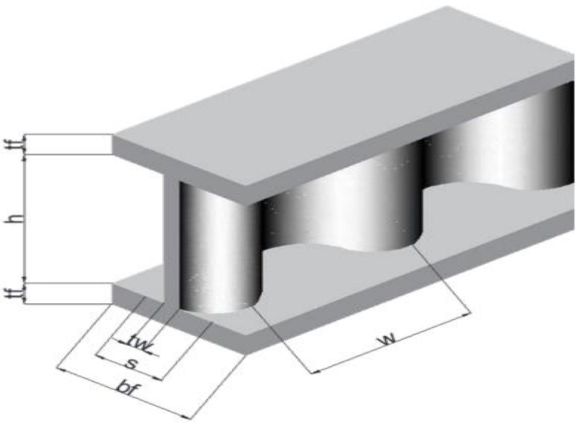


Fig. 1 Geometric properties of corrugated web beam

resistance of presently used sinusoidal corrugated webs is comparable with plane webs. The adoption of steel beam with corrugated web for mechanical performance of the structure has been studied by Sayed *et al.* (2001) and Jiang *et al.* (2015), respectively. This key feature has been demonstrated by Chan *et al.* (2002), Chen *et al.* (2015, 2016) and Wang *et al.* (2018) on the structural performances of composite girders with steel corrugated webs, including the flexural capacity, then searched by He *et al.* (2012), Hassanin *et al.* (2013, 2014), Mo *et al.* (2000, 2003), Ding *et al.* (2012) and Chen *et al.* (2016) including shear capacity, the torsional behavior and the dynamic properties of mentioned beams. Then, Lu and Ji (2018) investigated to optimize and improve the prestressed concrete composite box-girders with corrugated steel webs with two different ways. And then, an analytical model accounting for the interaction between the local and global shear buckling of corrugated steel web beams is proposed by Barakat and Leblouba (2018). Experimental results from that study are compared with the analytical model. Lastly, the long-term behavior of a three-span bridge with corrugated steel webbing has been examined by Zhan *et al.* (2019). In the present study, the ultimate load capacities of optimally designed composite corrugated web beams are tested in a self-reacting frame to perform critical loads for all tested specimens. For this purpose, six corrugated beams are tested to determine the ultimate load capacities of mentioned beams under loading conditions. The tested specimens are designed by using one of the stochastic search techniques called hunting search method. This meta-heuristic algorithm is successfully applied to the optimum design problems of structures where the design constraints are implemented from BS EN1993-1:2005 (Annex-D, Eurocode 3), BS-8110 and DIN 18-800 Teil 1-3 provisions. In this formulation, the thickness of concrete slab and studs, web height and thickness, distance between the peaks of the two curves, the width and thickness of flange in the composite corrugated web beams are considered as design variables. The computational steps of the algorithm and the design process are not demonstrated in the paper due to space limitations, yet the detailed implementation specifics of the search method and optimum design process of corrugated web beams can be found in Erdal *et al.* (2017) with parameter sets.

2. Design of composite corrugated web beams

The ultimate state design of a beam necessitates check of its strength and serviceability. The computation of the strength of a corrugated web beam is determined by considering the interaction of flexure and shear at the sinusoidal web. Consequently, the constraints to be considered in the design of a corrugated web beam include the displacement limitations, transverse force load capacity of webs, normal force load carrying capacity of flanges, lateral torsional buckling capacity of the entire span, rupture of the welded joint, formation of a flexure mechanism and practical restrictions for corrugated web and flanges mentioned in Erdal *et al.* (2016, 2017).

2.1 Stochastic optimization techniques

A combinatorial optimization problem requires exhaustive search and effort to determine an optimum solution which is computationally expensive and, in some cases, may even not be practically possible. Meta-heuristic techniques are established to make this search within computationally acceptable time period. Amongst these techniques are simulated annealing (Kirkpatrick *et al.* (1983)), evolution strategies (Rechenberg (1965)), particle swarm optimizer (Perez *et al.* (2007)), tabu search (Glover (1989)), ant colony optimization (Dorigo and Stutzleet (2004)), harmony search method (Lee and Geem (2004)), genetic algorithms (Goldberg (1989)) and others. All of these techniques implement particular meta-heuristic search algorithms that are developed based on simulation of a natural phenomenon into numerical optimization procedure. They have gained a worldwide popularity recently and have proved to be quite robust and effective methods for finding solutions to discrete programming problems in structural optimization.

2.1.1 Hunting search algorithm

Hunting search method based optimum design algorithm has six basic steps, which is outlined in the following (Oftadeh and Mahjoob 2010). In the first step design algorithm and parameters are initialized. *HGS* defines the group size which is the number of solution vectors in hunting group, *MML* represents the maximum movement toward the leader and *HGCR* is hunting group consideration rate which varies between 0 and 1. Then, hunting group is generated in the second step. On the basis of the number of hunters (*HGS*), hunting group is initialized with following equation by selecting randomly sequence number of sections (I_i) for each group.

$$I_i = \text{INT}[I_{\min} + r(I_{\max} - I_{\min})] \quad i = 1,\ldots,\text{n} \tag{1}$$

Where; the term r represents a random number between 0 and 1, I_{min} is equal to 1, I_{max} is the number of values in the discrete set and n is the number of design variables. In Step 3, hunters move toward the leader. New hunters' positions are generated by moving toward the leader hunter.

$$I_i^{'} = I_i + r \text{ MML } \left(I_i^L - I_i \right) \qquad i = 1,\ldots,\text{n} \tag{2}$$

Where; I_i^L is the position value of the leader for *i-th* variable. Then, position correction-cooperation between hunters is done in the fourth step. After moving toward the leader, hunters tend to choose another position to conduct `hunt' efficiently, i.e., better solutions. Position correction is performed in two ways, first one is real value correction and the other is digital value. In this study, real value correction is employed for the position correction.

$$I_i^{j'} \leftarrow \begin{cases} I_i^{j'} \in \left\{ I_i^1, I_i^2, \ldots, I_i^{HGS} \right\} \rightarrow HGCR \\ \text{INT} \left(I_i^{j'} = I_i \pm \text{Ra} \right) \rightarrow (1 - HGCR) \end{cases} \tag{3}$$

In the penultimate step, each member of hunting group must reorganize themselves to get another chance to find the global optimum. If the difference between the objective functions obtained by the leader and the worst hunter in the group becomes smaller than a predetermined constant (ε_1) and the termination criterion is not satisfied, then the group reorganized. By employing the Eq. (6), leader keeps its position and the others randomly select positions.

$$I_i^{'} = I_i^L \pm r \left(\max(I_i) - \min(I_i) \right) \alpha \left(-\beta \text{ EN} \right) \tag{4}$$

Where; I_i^L is the position value of the leader for the *i-th* variable, *r* represents the random number between 0 and 1, $min(I_i)$ and $max(I_i)$ are minimum and maximum values of variable I_i, respectively, *EN* refers to the number of times that the hunting group has trapped until this step. α and β are determine the convergence rate of the algorithm. Finally, third and fifth steps are repeated until a pre-assigned maximum number of cycles are reached for termination.

3. Optimum design problem

The design of a composite corrugated web beam requires the selection of width and thickness of a plate from which the corrugated web is to be produced, distance between the peak points of each corrugate, the length of corrugate web, the selection of width and thickness of a plate for upper and lower flanges in the beam, thickness of the concrete slab and connection members between the concrete slab and corrugated beam are considered as design variables. For this purpose, a design pool is prepared. The optimum design problem formulated considering the design constraints explained in the previous sections yields the following mathematical model. Find a integer design vector $\{I\} = \{ I_1, I_2, I_3, I_4, I_5, I_6, I_7\}^T$ where I_1 is the sequence number of for the width of upper and lower flanges, I_2 is the sequence number for the thickness of upper and lower flanges, I_3 is the thickness of corrugated web, I_4 is distance between the peak points of corrugate webs and I_5 the height of corrugate web, I_6 thickness of the concrete slab and I_7 is the connectors between the slab and corrugated beam. Hence the design problem turns out to be minimizing the weight of the composite beam (W_{kom}).

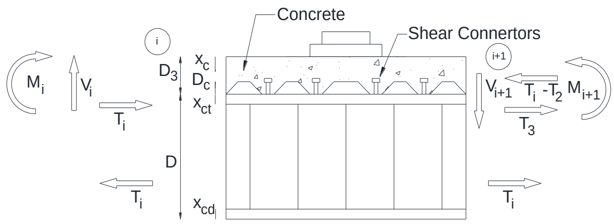


Fig. 2 The demonstration of composite corrugated web beam cross-section

$$W_{kom} = \rho_s \left(\left(2 \times b_f \times t_f \times L \right) + \left(h \times t_w \times L_{d\ddot{u}z} \right) \right) + \rho_{bet} \left[A_{bet} L + \left(A_{stu} N_{stu} \right) \right] \tag{5}$$

Where, ρ_S density of steel, b_f the width of flange, t_f thickness of flange, *L* span of beam, *h* height of corrugated web, t_w thickness of corrugated web and $L_{d\ddot{u}z}$ span of beam before corrugation process. P_{bet} the density of concrete class, A_{bet} the section area of the concrete slab, A_{stu} net section area of connection members between concrete slab and corrugated beam, N_{stu} the number of connection members between the concrete slab and corrugated beam along span. The demonstration of composite corrugated web beam under loading conditions is given in Fig. 2 with more detail.

Although some design parameters are left to the engineer, for web and flange dimensions, the following geometrical restrictions in Eqs. (6)-(9) are required to be observed, respectively.

$$333 \; mm \leq \; h \; \leq 1500 \; mm \tag{6}$$

$$1.5 \; mm \leq \; t_w \; \leq 5.0 \; mm \tag{7}$$

$$120 \; mm \leq \; b_f \; \leq 450 \; mm \tag{8}$$

$$6.0 \; mm \; \leq \; t_f \; \leq \; 30.0 \; mm \tag{9}$$

3.1 Transverse load carrying capacity of corrugated webs

Based on the experimental test results (*Test report on experiments carried out on I-beams with corrugated web plates* (1990) and *Final Report on the Bearing Performance of Corrugated Web Beams* (1996)) and DASt-Ri.015 (1990), the following design procedure for shear load bearing capacity (V_{TK-MAX}) has been suggested: An orthotropic plate with rigidities (D_x;D_y) in corrugated web should be checked in Eq. (10). For transverse buckling stress of corrugated web (τ_{EG}) Eq. (11), for slenderness parameter of corrugated web (λ_{GN}) Eq. (12), for the buckling coefficient of corrugated web (K_B) Eq. (13) and transverse force load carrying capacity for the corrugated web finally results in Eq. (14) (DASt-Ri.015).

$$D_x = \frac{E \times w \times t^3}{12 \times s}, D_y = \frac{E \times I_y}{w} \text{ for } D_x \leq D_y \tag{10}$$

$$\tau_{EG} = \frac{162}{5 \times t_w \times h^2} \sqrt{(D_x \times D_y^3)} \tag{11}$$

$$\lambda_{GN} = \sqrt{\frac{f_y}{\sqrt{3} \times \tau_{EG}}} \tag{12}$$

$$K_B = \frac{1}{(\lambda_{GN})^{3/2}} \tag{13}$$

$$V_{TK-MAX} = \frac{K_B \times f_y \times h \times t_w}{\sqrt{3}} \tag{14}$$

3.2 Normal load carrying capacity of flanges

It is necessary to check tensile and compressive stresses in corrugated beams (DIN 18800 Teil 1 and Teil 2). The first one is the tensile stress capacity of beam. The load capacity of the flange is derived in Eq. (15).

$$\sigma_{ALLOW} = \frac{N_{T-MAX}}{b_f \times t_f} \tag{15}$$

Reformulation of the expression for ψ = 1 leads to the following elastic limit stress

$$\sigma_{EL} = \frac{4000}{\left(b_f \times t_f\right)^2} \tag{16}$$

Therefore the reduced normal force on the flange

$$N_{NORMAL} = \sigma_{EL} \times b_f \times t_f \tag{17}$$

Failure of stability - lateral buckling of the flange - is equivalent to the verification against torsional-flexural buckling. If the restraining effect of the web is ignored, the torsional-flexural verification is carried out as the buckling verification for the "isolated" flange. The following condition for the distance between lateral supports is obtained

$$\tau_{EG} = \frac{\pi}{4\sqrt{3}} \sqrt{E \times f_y} \times \frac{b_f^2 \times t_f}{k_c \times c} \tag{18}$$

3.3 Behavioural and geometrical restrictions of composite beam

The moment capacity of composite corrugated web beam with sinusoidal web function (M_{RD}) has been defined as following equations. For the neutral axis on concrete slab

$$T_{AD} = A \times \frac{f_y}{\gamma_a} \text{ and } a = \frac{T_{AD} \times \gamma_c}{0.85 \times f_{ck} \times b_c} \tag{19}$$

$$M_{RD} = T_{AD} \times (d_1 + h_F + t_c - a/2) \tag{20}$$

For the neutral axis on steel profile

$$C_{CD} = 0.85 \times \frac{f_{ck}}{\gamma_c} b_c \times t_c \text{ and } C_{ad} = \frac{1}{2} \times (T_{AD} - C_{CD}) \tag{21}$$

$$M_{RD} = C_{AD} \times (d - y_t - y_c) + C_{CD}((t_c/2) + h_f + d - y_t) \tag{22}$$

In these equations, d height of steel section, d_1 distance between the center of steel section and upper part, y_c distance between the center of pressure region of steel section and upper part, y_t distance between the center of tension region of steel and lower part, t_c height of slab, b_c effective slab width, h_f height of steel deck, f_y yield strength of steel, f_{ck} compressive strength of concrete, γ_a and γ_c are coefficients for steel and concrete N_{stu}.

3.4 The design of concrete slab for corrugated web beams

The effective length of concrete slab and number of shear connectors have been calculated for *OGK_330*, *OGK_415* and *OGK_500* beams according to EC4, BS-5950 Part-3, Section 3-1.

$$b_{eff=} \frac{l_0}{4} = \frac{470cm}{4} = 117{,}5cm \tag{23}$$

$$R_S = 0{,}95 f_y A_a \tag{24}$$

In these equations, b_{eff} is effective length of concrete slab and l_0 is span of beam.

$$R_C = 0{,}45 f_{cu} b_{eff} h_c \tag{25}$$

In the equation 25, R_c is compressive force of concrete, h_c the depth of the concrete slab, A_a is section area of steel, h height of steel section, h_p the depth of concrete slab at tab of the deck. If plastic neutral axis is on the upper flange of steel section, moment is defined as

$$M_{pl,Rd} = R_S \frac{h}{2} + R_C \left(\frac{h_c}{2} + h_p\right) \tag{26}$$

The calculation of shear connectors for composite beams has been defined in equations 27, 28 and 29. In these equations, f_u maximum tensile stress of steel shear connectors, h the height of shear connectors, d the diameter of shear connectors, γ_v safety factor, and α is constant.

$$P_{Rd} = 0{,}29 \alpha d^2 \frac{\sqrt{f_{ck} E_c}}{\gamma_v} \tag{27}$$

$$P_{Rd} = 0{,}8 f_u \frac{\pi d^2}{4 \gamma_v} \tag{28}$$

$$\alpha = 0{,}2 \left(\frac{h}{d} + 1\right) \leq 1 \rightarrow \tag{29}$$

4. Design example

Optimum design algorithms presented are used to design a corrugated steel web beam (OGK) with 5-m span shown in Fig. 3. The beam is subjected to point loading. The upper flange of the beam is laterally supported by the floor system that it supports. The maximum displacement is limited to 17 mm. The modulus of elasticity is 205 kN/mm^2.

The design example is solved by hunting search (HSA). The maximum number of generations is taken as 5000 (Table 1).

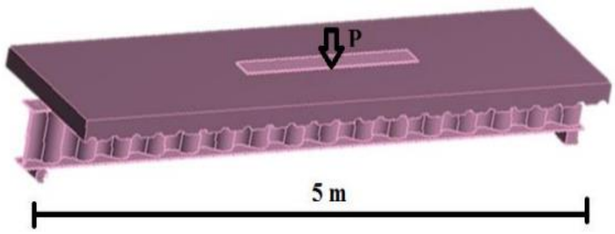


Fig. 3 Loading of 5-m span corrugated web beam

Table 1 The Parameters of HSA Technique

The values of parameters			
HGS	90	Ra_{max}	0.01
MML	0.002	Ra_{min}	*0*
HGCR *and α*	0.9	β=0.02	*IE=25*
IE	*25*	N_{cyc}	*5000*

Table 2 Optimum Design of Corrugated Beam with 5-m Span

Optimum Section	t_w (mm)	h (mm)	t_f (mm)	H_c (mm)	L_c (mm)	Weight (kg)
OGK_330	5	330	8	43	155	176.33
OGK_415	4	415	10	43	155	216.91
OGK_500	5	500	12	43	155	302.24

The result of the sensitivity analysis carried out for the HSA parameters is given in Table 2. In steel construction applications, the web part of beam usually carries the compressive stress and transmits shear in the beam while the flanges support the applied external loads. By using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the load-carrying capability of the beam. In this case, the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability and deforms transversely.

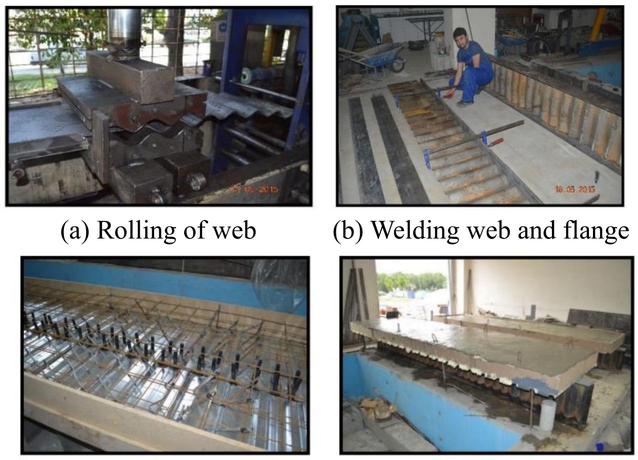
It is apparent from the table that HSA produces 176.33 kg weight for corrugated web beam OGK_330. The maximum value of the strength ratio is 0.98 which is almost upper bound. This reveals the fact that the strength constraints are dominant in the problem. The optimum corrugated web beam should be produced such that it should have 5 mm web thickness 330 mm web height, 8 mm flange thickness and 160 mm flange width. HSA also produces 216.9 kg and 302.24 kg weight for corrugated web beam OGK_415 and OGK_500, respectively. The dimensions of OGK_415 and OGK_500 beams are also given in Table 2.

5. Experimental tests on designed composite corrugated web beams

The experimental investigation was carried out on three different sets of composite beam specimens under different type of loadings. The ultimate load carrying capacities of optimally designed these mentioned beams (*OGKK*) are tested in a self-reacting frame. The tests have been carried out on six full-scale *OGKK_330, OGKK_415* and *OGKK_500* typebeams. These optimally designed simply supported beams which have preliminary span lengths of 5000 mm are subjected to point loading, two points loading and partially distributed loading, respectively. All specimens are placed on simple supports at both ends. A pair of lateral supports is provided at the end of each beam end for preventing lateral torsional buckling. The load is provided by hydraulic jack reacting on the laboratory floor and aligned equally on each side of the beam. The canister type load cell used for the experiments is calibrated before testing procedure took place. To record overall displacements of the corrugated beams, four transducers are mounted to test specimens. For each beam, the adjustment of loading rod positions has been applied. The purpose of this action is to prevent the eccentric loading. The main focus of the experiment is to investigate ultimate carrying capacity of composite corrugated web beams and to observe what type of failure would take place after compression tests on these beams.

5.1The fabrication process of composite corrugated web beams

Six optimally designed composite corrugated web beams (*OGKK_330, OGKK_415* and *OGKK_500*) fabricated are tested to find out ultimate load capacities of such beams. Rolling of the web parts (Fig. 4(a)), welding process of web and flanges (Fig. 4(b)), bolting of steel studs (Fig. 4(c)) and the preparation of floor formwork for concrete slab (Fig. 4(d)) are shown in Fig. 4, respectively.



(a) Rolling of web (b) Welding web and flange

(c) Anchor bolt (d) Concrete casting

Fig. 4 Fabrication processes of composite corrugated web beams

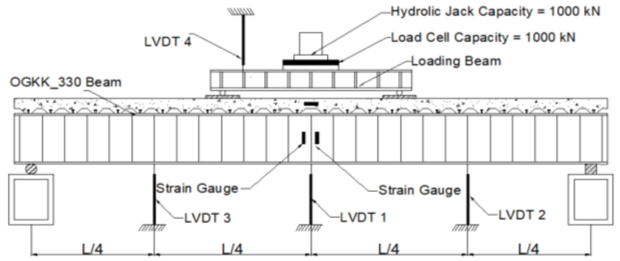


Fig. 5 Details of test set up for *OGKK_330* composite beams

Fig. 6 Flexural Bending on Composite OGKK_330

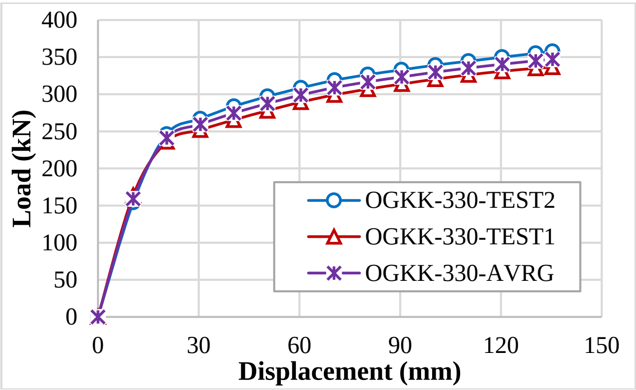


Fig. 7 The Load-deflection graphics for OGKK_330

5.2 Tests on composite corrugated web beams

In the first part of the tests, two optimally designed composite corrugated beams fabricated from *OGKK_330* sections are tested to find out ultimate load capacities of such beams. These two simply supported composite test beams which have the same dimensions are subjected to two-point loading. The test set up for *OGKK_330* section is illustrated in Fig. 5.

The results obtained from experimental tests on *OGKK_330* beams demonstrate that beams have failed under the applied values of 342.07 kN and 359.54 kN, respectively (Fig. 6).

Ultimate load capacities of OGKK_330 steel corrugated web beams are found as 140.36 kN and 188.78 kN at the member tests on steel corrugated web beams in Erdal *et al.* (2016).

Afterwards, installing a reinforced concrete slab over these beams increases the capacities of such beams %243.7 and %190.5, respectively. The results obtained from tests on *OGKK_330* section beams demonstrate that all of the beams failed from flexural bending as revealed in Fig. 7.

In the second part of the tests, two optimally designed composite corrugated beams fabricated from *OGKK_415* sections are tested to find out ultimate load capacities of such beams. These two simply supported composite test beams which have the same dimensions are subjected to partially distributed loading. The test set up for *OGKK_415* section is illustrated in Fig. 8.

The failure of *OGKK_415* having achieved its ultimate loads 478.36 kN and 492.83 kN under partially distributed loading over slab is described as flexural bending and illustrated in Fig. 9.

Ultimate load carrying capacities of OGKK_415 steel corrugated web beams are found as 215.5 kN and 205.94 kN at the member tests on steel corrugated web beams Erdal *et al*. (2016).

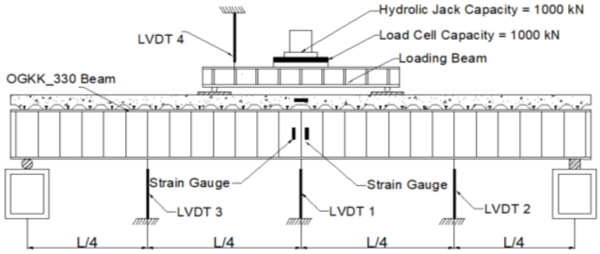


Fig. 8 Details of test set up for *OGKK_415* composite beams

Fig. 9 Flexural bending on composite OGKK_415

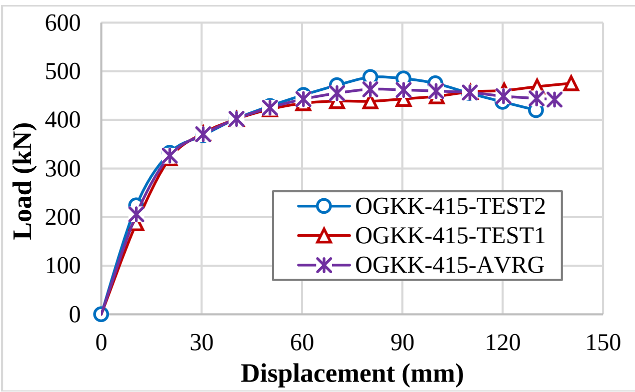


Fig. 10 The Load-deflection graphics for OGKK_415

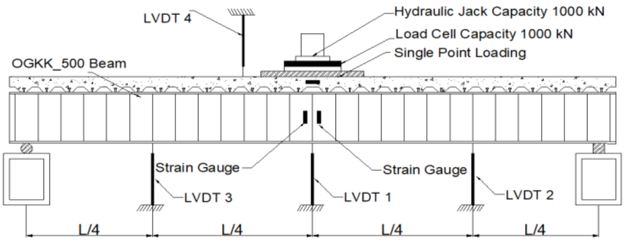


Fig. 11 Details of test set up for *OGKK_500* composite beams

Fig. 12 Flexural bending on composite OGKK_500 corrugated web beam

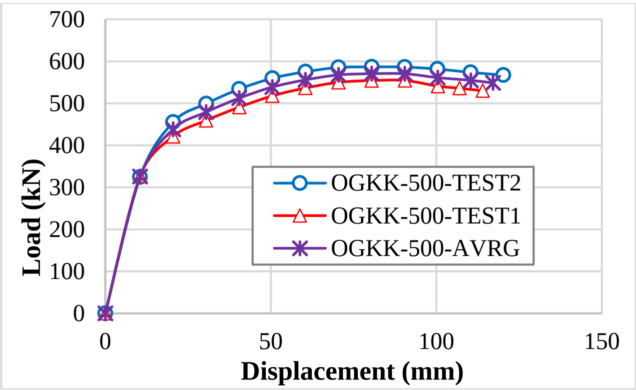


Fig. 13 The Load-deflection graphics for OGK_500

Afterwards, installing a reinforced concrete slab over these beams increases the capacities of such beams %221.9 and %239.3, respectively. The results obtained from tests on *OGKK_415* section beams demonstrate that all of the beams failed from flexural bending as revealed in Fig. 10.

In the last part of tests, optimally designed composite beams fabricated from *OGKK_500* are tested to find out load capacities of such beams. These two simply supported composite test beams which have the same dimensions are subjected to single concentrated loading at the middle part of the composite beam. The test set up for *OGKK_500* is illustrated in Fig. 11.

Fig. 12 shows that the results obtained from tests on *OGKK_500* beams demonstrate that beams have failed under the applied values of 561.05 kN and 587.84 kN, respectively.

Ultimate load capacities of *OGK_500*beams are found as 277.04 kN and 294.21kN at the member tests on steel corrugated web beams (Erdal *et al*. 2016). Afterwards, installing a reinforced concrete slab over these beams increases the capacities of such beams %202.5 and %199.8, respectively. The results obtained from tests on *OGK_500* section composite beams demonstrate that all of the beams failed from flexural bending as revealed in Fig. 13.

5.3Tensile and compressive tests on specimens

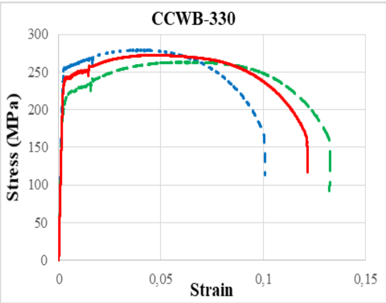
The objective of tensile and compression experiments is to determine the yield stress, ultimate stress and modulus of elasticity properties of different steel profiles from standard test specimen and to describe compressive strength of concrete slab (Fig. 14).

ASTM E 8M-04 is applied in the standard tensile test of steel rectangular test specimen and ASTM C39/C39M is also provided standard test method for compressive strength of cylindrical concrete specimens, respectively. Observed data from tensile tests were used to calculate the tensile strength of specimens, and at the same time, converted and plotted a stress–strain curve for each specimen and determine the values indicated above and to compare test results with materials. These stress–strain graphs are then used in determination of the modulus of elasticity of the specimens. For this purpose, the slope of the elastic region of these curves is determined by fitting a straight line, with the least-square method. Stress–strain graphs for each specimen of steel beams plotted in MS Excel are demonstrated respectively in Figs. 15(a)-15(c).

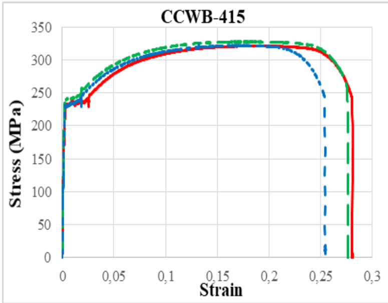
Using the stress–strain graphs in Figs. 15(a)-15(c), in this study, the average value of elasticity modulus is determined as 1.92×10^5 MPa. After the tension tests, the average values of yield strength are respectively determined as 240 MPa, 235 MPa and 220 MPa for *OGKK_330*, *OGKK_415* and *OGKK_500* steel sections. In addition to these values, Poisson ratio is taken as 0.3 for each steel section. Modulus of elasticity, Poisson ratio, yield and ultimate strength values found at tensile tests are used in FEA of corrugated beams.

After the compression tests, ultimate load capacities of tested cylindrical concrete samples are determined as 386.2 kN, 383.3 kN and 343.8 kN, respectively. The average value of compressive strength is determined as 371.1 kN on the basis of test of cylindrical samples.

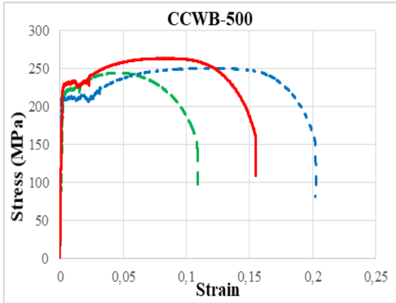
Fig. 14 Tension and compression tests on *OGKK* specimens



(a) OGK_330



(b) OGK_415



(c) OGK_500

Fig. 15 Stress-strain graph of tensile tests of corrugated steel web beam specimens

6. Finite element analysis of composite corrugated web beams

The objective of this section is to carry out non-linear finite element analysis of the composite corrugate web beams that were considered in the experimental study in order to determine their ultimate load capacity for comparison. FE method has been used to predict their entire response to increasing values of external loading until they lose their load carrying capacity. These finite element models are used to simulate the experimental work in order to verify of test results and to investigate the non-linear behavior of failure modes of *OGKK_330*, *OGKK_415* and *OGKK_500* type composite corrugate web beams. Finite element analysis was carried out on composite beams with corrugated webs using the finite element software *ANSYS*-Workbench in this study. Three-dimensional finite element models of these beam specimens are built to determine maximum values and locations of stress, strain and displacement concentrations under loading conditions. The objective of these analyses is to determine stress, strain and displacements in the *OGKK* and to compare experimental results with the results of observed nonlinear analyses. Based on these analyses, proper locations for the instalment of transducers in the *OGKK* sections are determined.

6.1 Element and material modelling on ANSYS program

During FEA process, structure is divided into small elements to calculate individual deformation easily.

Tetrahedron volume is selected in the modelling of composite corrugated web beams. These elements are composed of 10-node high-order element types and every node of this volume has three degrees of freedom. In this study, this element has also quadratic displacement behavior and is well suited to model irregular meshes comparing with other types. For 3-D analysis of beams, one of the contact surface elements *CONTA-174* is selected to represent contact and sliding between 3-D target surfaces and a deformable surface given that it is defined as a higher-order element. The element is applicable to 3-D structural and coupled field contact analyses. This element is defined by eight nodes and is located on the surfaces of 3-D solid or shell elements with mid-side of nodes. For the target segment, *TARGE-170* is selected to represent various 3-D target surfaces for the contact surface elements.

6.2 Mesh generations on composite corrugated web beams with ANSYS

In this study, automatically generated, tetrahedrons and hex-dominant meshing types are tested for *FEM* of composite corrugated web beams to compare their created nodes and elements for the same mesh sizing. In this purpose, *OGKK_330* type beam is used to mesh with these generation types. Mesh size is taken as 100 mm for each method. It is observed from Table 3 that when all meshing methods give different values for nodes and elements.

When the mesh type is taken as automatically-generated for 100 m mesh size, beam consists of 25300 elements and 53732 nodes. For the same mesh size, hex–dominant consists of 22616 elements and 55116 nodes. In comparison with other types, tetrahedron meshing provides better size distribution for the beam across the model with 29531 elements and 56957 nodes. Therefore, tetrahedron meshing option is selected for solving the all models. Consequently, an accurate simulation of the nonlinear behavior is obtained. Mesh sizing is important for accurate stress and displacement values. For this purpose, tetrahedron mesh divides various sizing mesh starting from 300 mm. When the stress and displacement values are stable, this mesh sizing can be applicable for FEM analysis. Fig. 16 illustrates that mesh sizing is important to find exact stress values.

Fig. 16 also demonstrates that maximum stress values (325.55 MPa and 336.39 MPa) on the corrugated web beam are nearly the same as the taken mesh sizes of 25 mm and 10 mm. It means 10 mm mesh size can be used for FEM analysis of these beams shown in Fig. 17.

Table 3 The number of nodes and elements for different mesh types

Mesh Type	Number of Nodes	Number of Elements
Automatically Generated	53732	25300
Hex-Dominant	55116	22616
Tetrahedrons	56957	29531

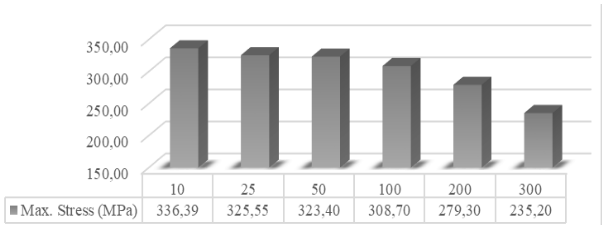


Fig. 16 Different mesh sizes and stress values

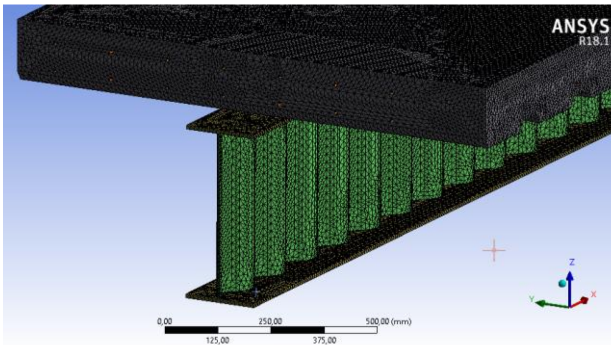


Fig. 17 Tetrahedron mesh model with 10-mm size

6.3 Nonlinear finite element model of composite corrugated web beams

The main objective of the nonlinear FEA is to determine stress, strain and displacements in the composite corrugated web beams and to compare test results with the results of observed nonlinear analyses. Nonlinear static analyses produce more accurate stress results than linear static analyses for models where the loading results in concentrated stress values beyond the material yield point and also nonlinear analyze give more real behavior when compared with the linear ones. Based on these analyses, proper locations for the installment of transducers in the *OGKK_330*, *OGKK_415* and *OGKK_500* elements are determined.

6.3.1Nonlinear solution of OGKK_330

The first part of nonlinear FEA of composite corrugated beams focuses on *OGKK_330.* 135.32 mm displacement, the average value obtained from experimental tests of composite beams, is applied to the beam at 10 steps and each step is applied to the beam with equal incremental displacement. As explained in the previous section, when this value is applied to a particular point, it stays inside meshes and sinks; consequently, *ANSYS* program does not analyze the composite beam model. For that reason, two point loading is applied to the mentioned composite beams as pressure as shown in the Fig. 18(a). Fig. 18(b) demonstrates that maximum displacement occurred in the middle of the beam as expected with a 142.55 mm for beam.

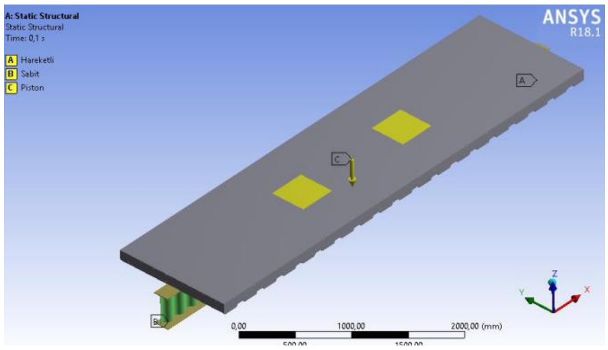
An isotropic material with Von-Mises yield criterion was used for the composite beam model the nonlinear material behavior of the beam. The material properties used in the *OGKK* section beam models were determined through tensile tests of coupons taken from the tests for steel members and compression tests of core samples taken from slabs. Since the main objective of this FEA was to determine failure behavior in corrugated web post regions, significant attention was paid on properly modelling the connection of the composite beam to the loading frame. When the maximum displacement obtained from experimental study, 135.32 mm, is applied to the beam by virtue of two-point loading, maximum equivalent stress which is 336.39 MPa, shown in Fig. 19(a), occur upper part of the flange.

When the same displacement value is applied to the beam maximum shear stress occurred at corrugated web part with the value of 103.80 MPa (Fig. 19(b)). It is observed from the Figs. 20(a) and 20(b) that maximum stress and force values on *OGKK_330* slab and reinforcement mesh are 19.95 MPa and 17.34 kN, respectively.

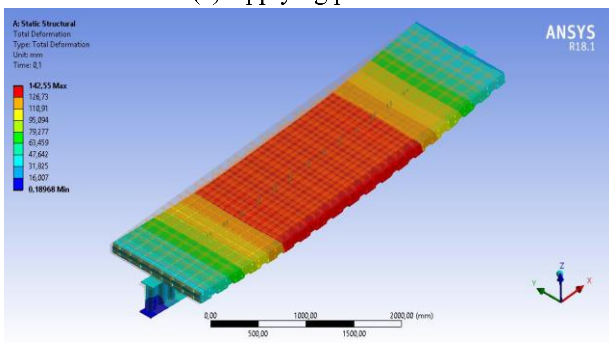
According to Fig. 21, the ultimate axial load carrying capacity from the finite element analysis of *OGKK_TEST_1* is 370.76 kN compared to 347.02 kN average value from the experimental tests which has 6.84% overestimation by finite element analysis. Fig. 21 also demonstrates that the result obtained from the finite element analysis is close to the one from the experiment.

6.3.2 Nonlinear solution of OGKK_415

In the second part of nonlinear FEA, 135.49 mm displacement for *OGKK_415*, the average value obtained from experimental tests of these composite corrugated web beams, is applied at the middle of the slab as partially distributed load in 10 steps as pressure (Fig. 22(a)).

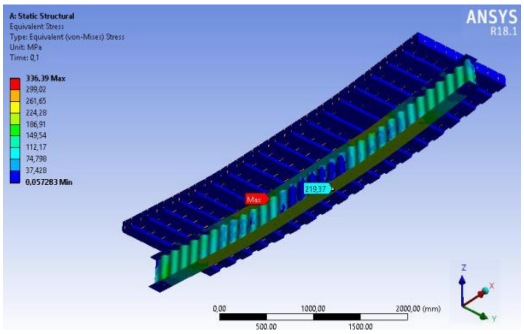


(a) Applying pressure

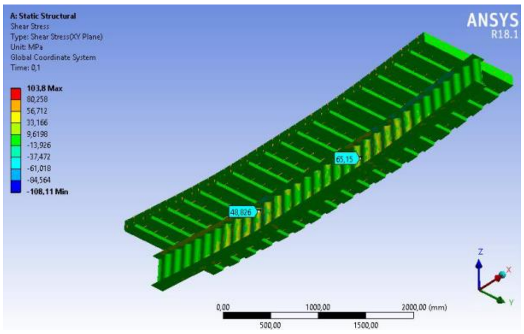


(b) Deformation values

Fig. 18 Applying force and deformation values on OGKK_330

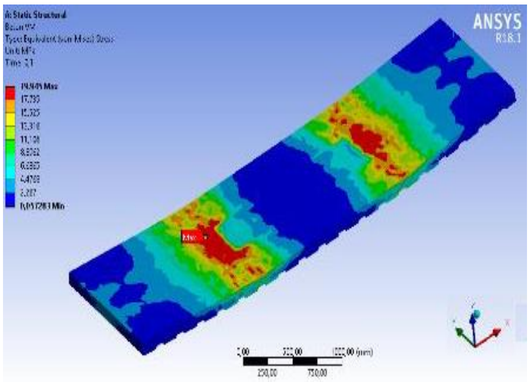


(a) Equivalent stress

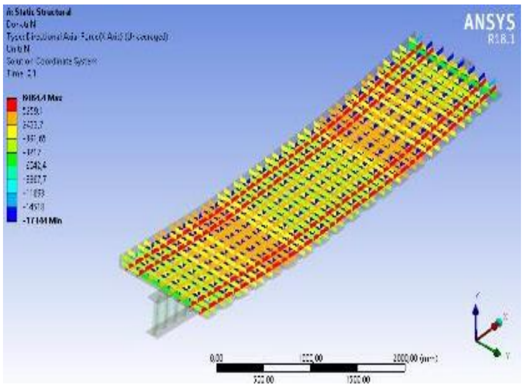


(b) Shear stress

Fig. 19 Stress values on OGKK_330



(a) Equivalent Stress



(b) Directional Axial Force

Fig. 20 Stress and force values on OGKK_330 slab and reinforcement mesh

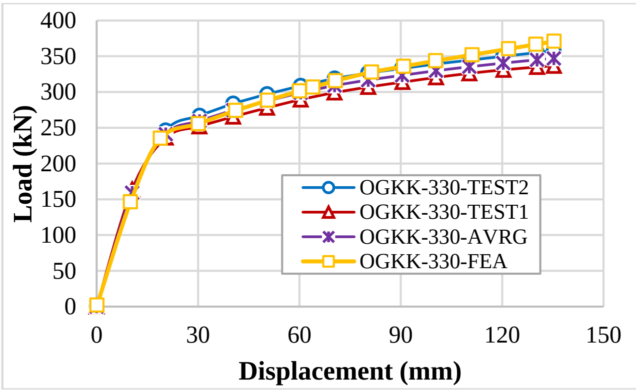
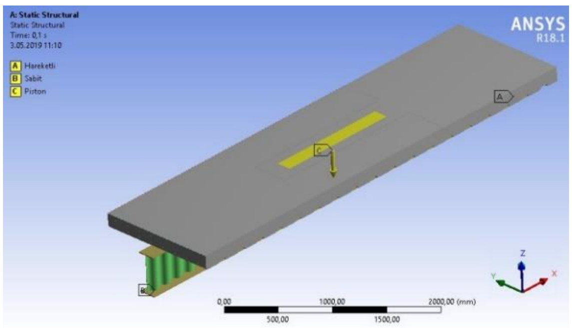
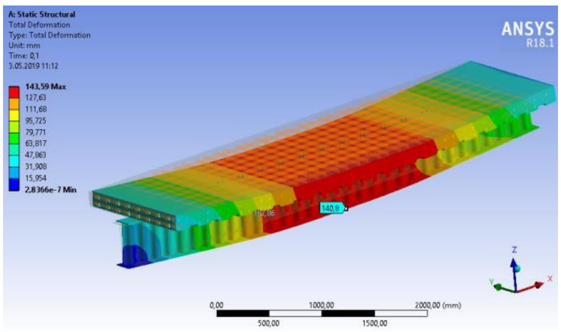


Fig. 21 Load-deflection curve for experimental and FEA results on OGKK_330

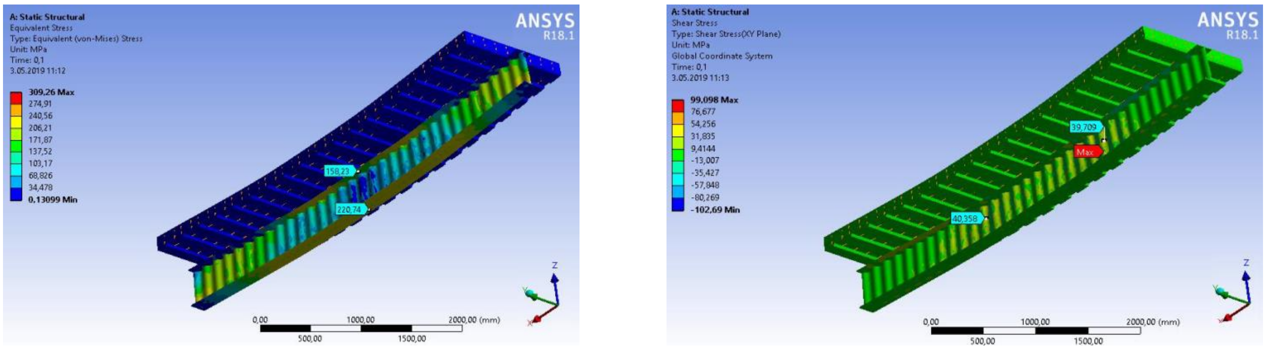


(a) Applying pressure



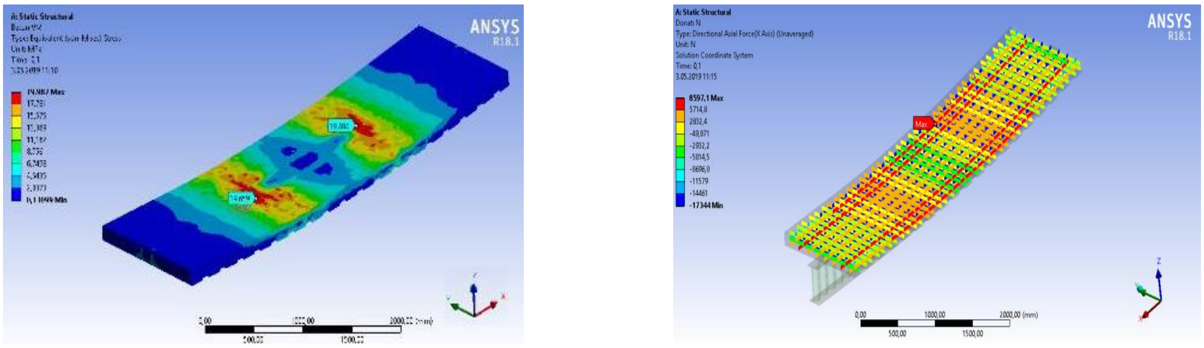
(b) Deformation values

Fig. 22 Applying force and deformation values on OGKK_415



(a) Equivalent Stress (b) Shear Stress

Fig. 23 Stress Values on OGKK_415



(a) Equivalent Stress (b) Directional Axial Force

Fig. 24 Stress and Force Values on OGKK_330 Slab and Reinforcement Mesh

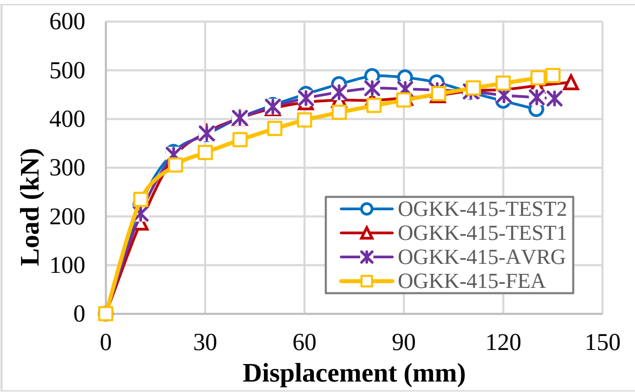
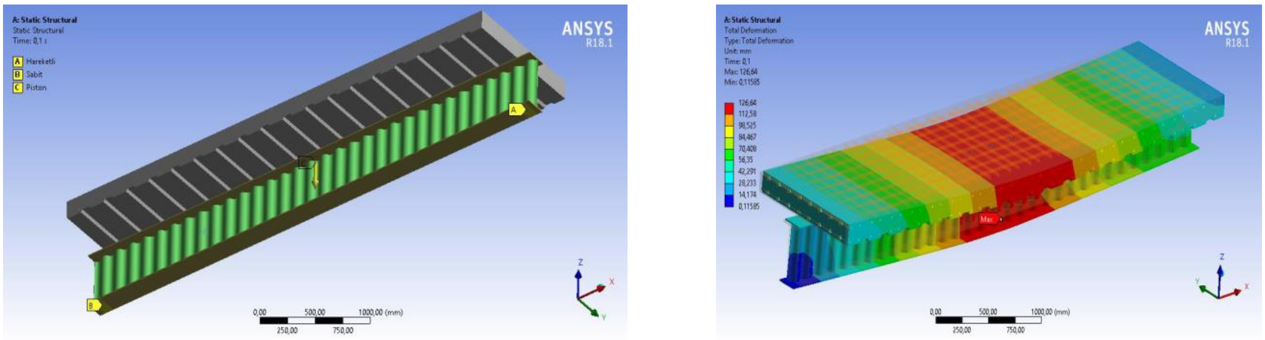


Fig. 25 Load-deflection curve for experimental and FEA results on OGKK_415

Figs. 24(a) and 24(b) clearly shows that maximum stress and force values on *OGKK_415* slab and reinforcement mesh are found as 19.98 MPa and 17.34 kN under applied same point loading. According to Fig. 25, the average value of experimental results, 447.81 kN, is compared with those of nonlinear solution values, 488.86 kN, it is found that the average load value obtained in *OGKK_415* is 9.16% less than the nonlinear displacement value.

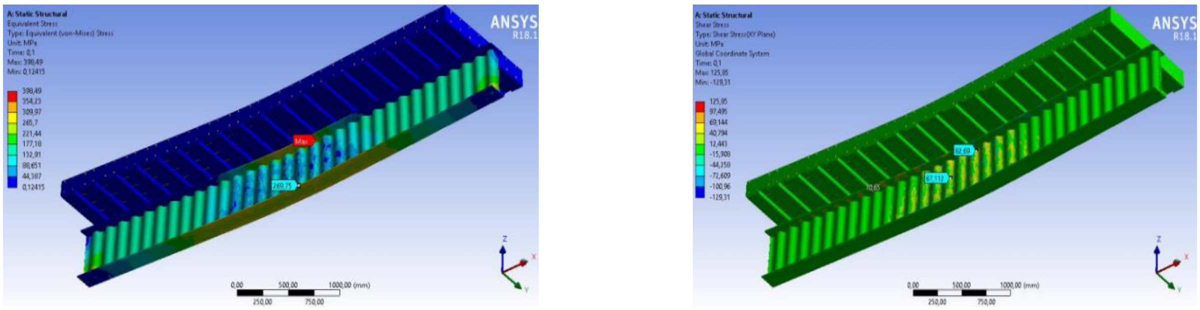
6.3.3 Nonlinear Solution of OGKK_500

Lastly, 117.13 mm displacement for *OGKK_500*, the average value obtained from experimental tests of these composite corrugated web beams, is applied at the middle of the slab as point load in 10 steps. When obtained value from tests was applied to the middle of the beam as shown above, maximum equivalent stress occurred at the middle part of upper flange (Fig. 27(a)). It was determined as 398.49 MPa after the application of load in 10 steps and the maximum displacement occurred in the middle of the upper flange as expected with a 126.64 mm for beam (Fig. 26(b)). When the same average value is applied to the middle part of the *OGKK_500*, maximum shear stress which is 125.85 MPa shown in Fig. 27(b), occurred around corrugated web part of the beam.



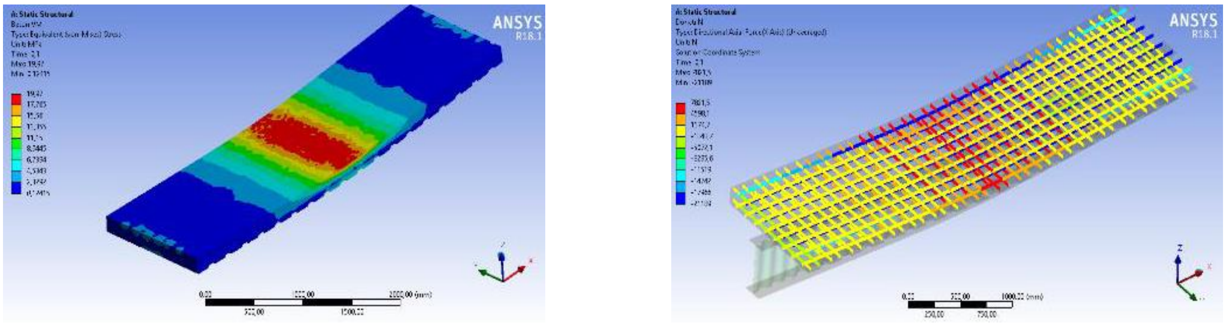
(a) Applying pressure (b) Deformation values

Fig. 26 Applying force and deformation values on OGKK_500 Beam



(a) Equivalent Stress (b) Shear Stress

Fig. 27 Stress values on OGKK_500



(a) Equivalent Stress (b) Directional Axial Force

Fig. 28 Stress and force values on OGKK_500 slab and reinforcement Mesh

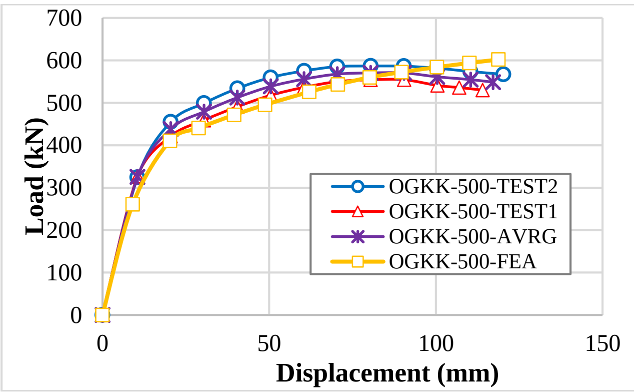


Fig. 29 Load-deflection curve for experimental and FEA results on OGKK_500

The maximum stress and force values shown in Figs. 28(a) and 28(b) for *OGKK_500* slab and reinforcement mesh are found as 19.98 MPa and 17.34 kN under applied point loading. According to Fig. 29 the average value of experimental results, 576.65 kN, is compared with those of nonlinear solution values, 602.82 kN, it is found that average load values obtained in *OGKK_500* is 4.53% less than the nonlinear displacement value. It is also shown in Fig. 29 that the result obtained from the finite element analysis for *OGKK_500* is so close the one from the experimental results.

7. Conclusions

In this research, a combination of experimental and finite element analysis method was applied to study the performance of optimally designed composite corrugated web beams under the action of different loadings in a self-reacting frame. The tested beams are designed by using hunting search optimization method. A total of six composite beams varying in the corrugation profiles and dimensions were tested under two-point, single point and partially distributed loading, respectively. It means that the compression flange of the corrugated web beams is sufficiently restrained by the floor system. In construction application using I-section beam, the thin web usually bears most of the compressive stress and transmits shear in the beam while the flanges support the major external loadings. Thus, by using greater part of the material for the flanges and thinner web, materials saving could be achieved without weakening the ultimate load-carrying capability of the steel and composite beams. Nevertheless, as the compressive stress in the web has exceeded the critical point prior to the occurrence of yielding, the flat web loses its stability and deforms transversely. Experimental tests on *OGKK_330, OGKK_415* and *OGKK_500* composite corrugated web beams showed that this can be achieved by using corrugated web, an alternative to the plane web, which produces higher stability and strength without additional stiffening and use of larger thickness.

The experimental work is also simulated by using *ANSYS*-workbench finite element integrated software program to verify the test results and to a good degree with the non-linear behaviour of failure modes of *OGKK_330, OGKK_415 AND OGKK_500* type composite beams. Failure loads obtained from experimental tests are compared with finite element analysis values for these three composite beams with corrugated web. Load-deflection diagrams shown in the study reveal that average deflection values obtained from experimental tests for *OGKK_330* type composite beams under 347 kN load is 6.84% lower than finite element analyse results which is within the acceptable range. Moreover, the failure loads obtained from experimental tests are compared with finite element analysis values for *OGKK_415* type composite beam. The load-deflection diagrams shown in the study also reveal that average deflection values obtained from experimental tests for lower flange of *OGKK_415* under 447.81 kN load is 9.16% more than from FEA results which is again within the reasonable range. Finally, obtained failure loads from experimental tests are also compared with FEA values for *OGKK_500*. The load-deflection diagrams related with *OGKK_500* type composite corrugated web beam illustrated in the study reveal that average deflection values obtained from experimental tests for lower flange of *OGKK_500* under 576.65 kN load is 4.53% less than from FEA results which is the closest value obtained between them. These results demonstrate that the nonlinear analysis results correlate well with experimental ones and the discrepancies are within 10%. This approximation is within the acceptable accuracy and it is concluded from the verification study that the proposed finite element modelling is completely capable of predicting the behaviour of the composite corrugated web in the study.

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