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ANALYSIS OF A COMPOSITE CONTINUOUS GIRDER WITH A SINGLE RECTANGULAR WEB OPENING

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Abstract: In this paper, a non-linear finite element analysis has been done to analyze the deflection in the steel section and internal stresses in the concrete slab for continuous composite girders with rectangular opening in the steel web. ANSYS computer program (version 14.5) has been used to analyze the three-dimensional model. The reliability of the model was demonstrated by comparison with experimental results of continuous composite beam without opening in the steel web carried out by another author. The parametric analysis was executed to investigate the width, height, and position of the opening in one span on the behavior of composite girder under vertical load. The results indicated that when the width of opening less than 0.05 of length of single span and the height less than 0.15 of steel web, the deflection and internal stresses increased less than 10 % comparing to continuous composite girders without opening.
Keywords: Composite steel-concrete girders, finite element analysis (FEA), web opening, shear connection, the effective width

INTRODUCTION

The use of composite steel beams with regular web-openings is becoming increasingly popular in multi-story building construction [1-3]. Openings are provided in the beam webs so that services could pass through the webs. In highway bridges and ship structures web openings in girders are provided in order to lighten the structure and to enable space for services, inspection and maintenance [4-7]. This form of construction results in reduced floor height, systematic installation of pipes or ducts and cost effectiveness but at the same time, causes penalty on the shear strength of the girders depending on the parameters of the openings [2,8]. The behavior of the composite girders (concrete slab-steel girder) has been the subject of several researches all over the world [9].

It is widely known that laboratory tests require a great amount of time and, in some cases, can even be impractical [10]. The finite element method (FEM) can be used as a very useful tool in predicting the failure load of composite concrete-steel beams and can allow very detailed information for the distribution of stresses and strains in composite beams [10-12]. Ibrahim et al. [13] used a finite element model to study the behavior of simple prestressed composite beams by means of a developed computer program (ANSYS 12) and compared the numerical results to the experimental results. The numerical results showed that the behavior in the concrete slab and steel beam responded well with the experimental results. Patil and Shaikh [14] presented 3D numerical models of steel-concrete composite beams to simulate their structural behavior with emphasis on the beam-slab interface. Simulations were occurred using version 14.0 of the ANSYS code, based on the FEM. The results were compared with those provided either by standards, experimental work, or found in the literature, and such comparisons demonstrated that the numerical approach followed is a valid tool in analyzing steel-concrete composite beam. A detailed literature review showed that the studies mostly focused on the behavior of simple composite girder with opening in steel web. Also the review showed that a little information available on the structural analysis of composite continuous girders with rectangular openings in the steel web. Therefore, the present study is concerned with the behavior of this type of structure using FEM.

FINITE ELEMENT MODEL

The analysis of continuous composite girders with rectangular opening in the steel web was performed using ANSYS computer program (version 14.5). Model components encountered throughout the current study, corresponding finite element representation and corresponding elements designation in ANSYS are presented as follows:

Element type selection

The three-dimensional element SOLID 186 is adopted to discretize the concrete slab, which is able to simulate cracking behavior of the concrete under tension (in three orthogonal directions), crushing in compression and evaluate the material non-linearity and enable the coverage of reinforcement (reinforcement bars scattered in the concrete region). The steel section is modeled using the SHELL 43 element, which facilitates non-linearity of the material and shows linear deformation in the plane in which it is present. The modeling of the shear connectors is done by the BEAM 189 element, which allows the configuration of the cross-section enables consideration of the non-linearity of the material and includes bending stresses. The TARGE 170 and CONTA 173 elements are used to represent the contact slab-beam interface. These elements can simulate the existence of pressure between them in the case of contact and separation between them in the case of no contact. The slab-beam contact materials also take into account slipping and uplift between the parties.

Material modeling

In this study, the main components of the composite section are modeled with relevant ANSYS elements as follows:

=   **Modeling of concrete**

The concrete is considered to be homogeneous and initially isotropic. The adopted stress-strain (f_c-☐ relation is based on work done by Desayi and Krishnan [15] as shown in Figure 1.
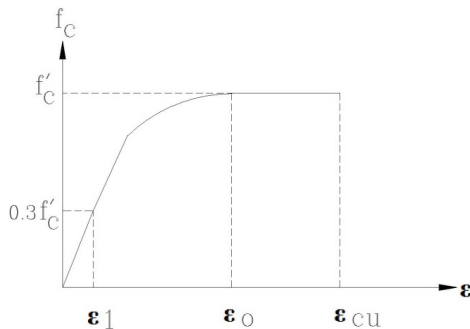

Figure 1. Compressive stress-strain curve for concrete used in ANSYS model

A compressive uniaxial stress-strain relationship for the concrete model was obtained by using Eqs. (1-4) to compute the multilinear isotropic stress-strain curve for concrete.

$$f_c = \varepsilon E_c \quad for \quad 0 \leq \varepsilon \leq \varepsilon_1 \qquad (1)$$

$$f_c = \frac{\varepsilon E_c}{1 + (\frac{\varepsilon}{\varepsilon_o})^2} \quad for \ \varepsilon_1 \leq \varepsilon \leq \varepsilon_o \qquad (2)$$

$$f_c = f_c' \quad for \quad \varepsilon_o \leq \varepsilon \leq \varepsilon_{cu} \qquad (3)$$

$$\varepsilon_1 = \frac{0.3 f_c'}{E_c} \quad (Hooke's\ law) \qquad (4)$$

$$\varepsilon_o = \frac{2 f_c'}{E_c}$$

where, $\varepsilon 1$ = strain corresponding to ($0.3 f_c'$), εo = strain at peak point, εcu = ultimate compressive strain.

=   **Modeling of steel girder**

The bilinear stress-strain relationship indicated in Figure 2 is used in this study [16]. The strain hardening modulus (E_t) is assumed to be ($0.03 Es$). This value is selected to avoid convergence problems during iteration.
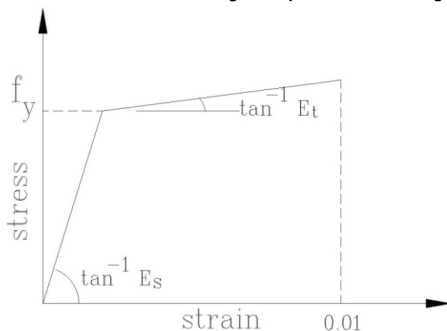

Figure 2. Stress-strain curve for steel girder used in ANSYS model

=   **Modeling of shear connectors**

The equation used to model the behavior of the shear connectors is:

$$F_d = F_{du}(1 - \frac{1}{e^{\Delta u_s}})^O 0.558$$

$$(5)$$

where, F_d is the dowel force, ΔUs = tangential displacement (mm), F_{du} = ultimate dowel force (Millard-Johnson Equation) given by [17]:

$$F_{du} = 1.3\phi^2 \sqrt{1.2 f_c' f_y}$$

$$(6)$$

where, $\emptyset$ is the diameter of the stud.

### Geometrical modeling and finite element meshing

The numerically modeled girders are typically composed of continuous girders with two equal spans as previously discussed. The model is defined by four types of elements that form the concrete slab with added reinforcements, steel girder, and shear connectors. The elements are established separately, but the nodes are coupled one by one on the interface between them. The finite element mesh developed followed the same methodology and degree of refinement presented in Figure 3(a-d).
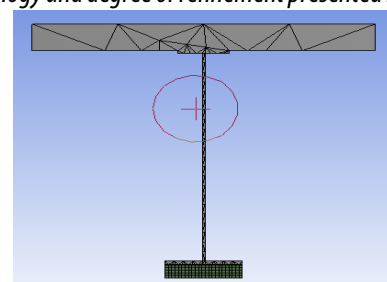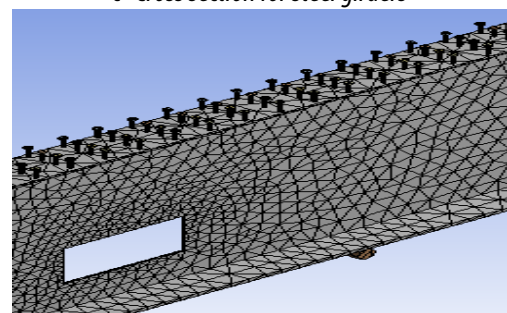

a- Cross section for composite girders
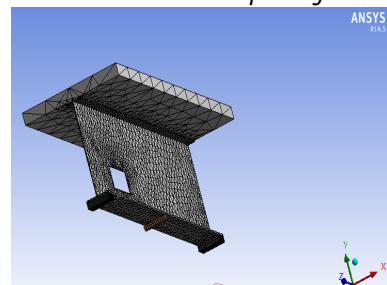
b- Continuous composite girder
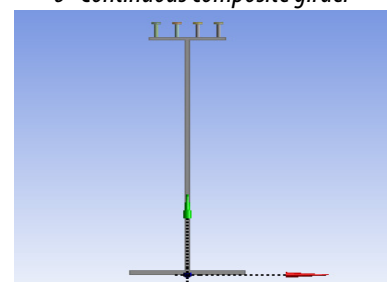
c- Cross section for steel girders

d- Continuous composite steel girders
Figure (3 a-d). Finite element model

THE VALIDATION OF THE MODEL

The validation of the model was examined by comparison with experimental results of continuous composite girders without opening in the steel web carried out by Arizumi, and Hamaha [18]. The parameters and material properties of the continuous composite beam are shown in Figure 4 and Table 1.

Table (1). Material properties for continuous composite beam

Concrete Slab			Steel Girder	
E_c (GPa)	f_c' (MPa)	F_t (MPa)	E_s (GPa)	f_y (MPa)
27.70	48.30	4.83	207.70	302.25

Figs. 5-7 indicate the experimental and analytical results of deflection distribution, strain distribution at bottom flange of steel section and slipping distribution between steel section and concrete slab for continuous composite beam. It is shown from these figures that the results obtained by finite element solution have a good agreement with experimental results.
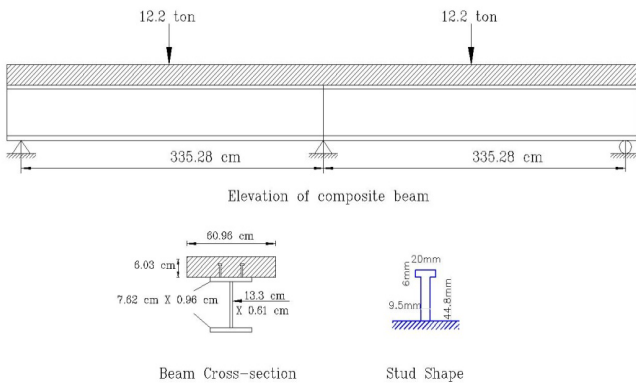

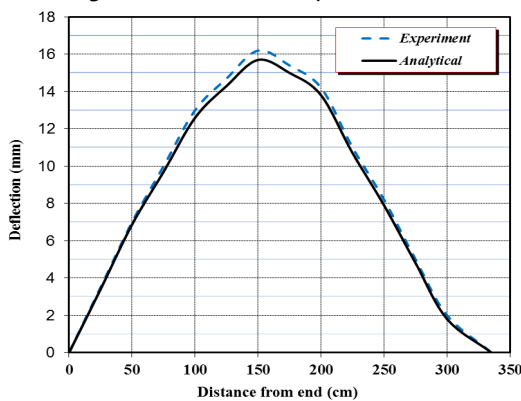**Figure 4** . Continuos composite beam

Figure 5. Deflection distribution for continuous beam (to one span)
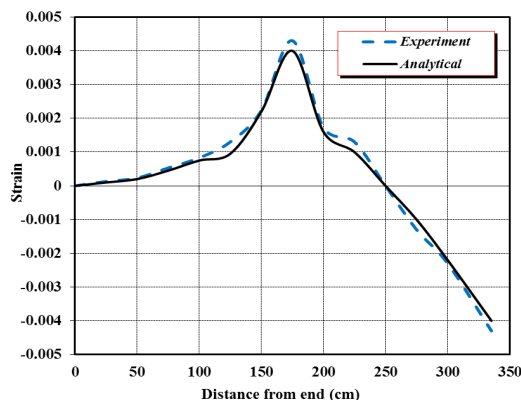

Figure 6 . Strain distribution at bottom flange of steel beam
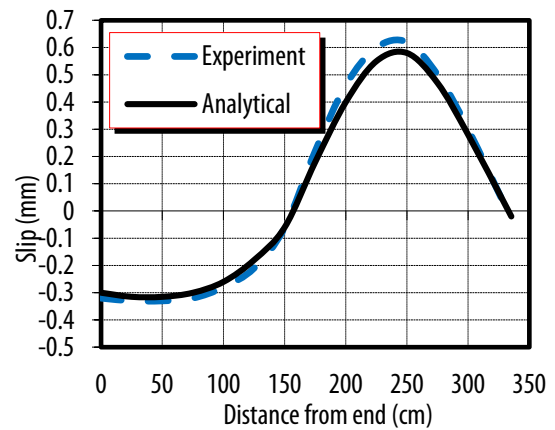

Figure 7. Slipping distribution between concrete slab and steel beam

PARAMETRIC STUDY

In this study, continuous composite girders two equal span with constant T-section are used as shown in Figure 8. The opening was made in the steel web of the left span while the right span was kept solid. The material properties of the steel and concrete are given in Table 2 where Ec and Es are the modulus of elasticity of the concrete and steel respectively, fc' is the concrete cube strength, and fy is the steel yield stress. The cross-section of the girder is shown in Figure 9 and the dimensions of the cross-section are given in Table 3. Throughout this study, it is assumed that the material of the composite girders (concrete slab and steel beam) is homogeneous, isotropic and linear elastic. The analysis was carried out using a finite element computer program (finite element modeling package ANSYS 14.5).

For a rectangular opening, the height (d) of the rectangular openings ranged from 0.05H

to 0.50H, where H is the depth of the steel I-section. The width (b) of the selected opening ranged from 0.02L to 0.15L, where L is the span length. Several positions of openings in the left span are studied.

Effect of opening height on the relative vertical deflections

Figures 10-13 show the effect of opening height d, for b = 0.10L and 0.15L, on the relative vertical deflections (maximum deflections of the two spans relative to the corresponding deflections of the solid composite girder, Δ1/Δs and Δ4/Δs respectively) of the two spans. These Figures show that when the opening height increases, the deflections Δ1 and Δ4 increase, especially when the opening is located close to the interior support. When the opening is located at mid-span, the deflection Δ1 increases and Δ4 decreases. From these Figures we obtain that, for small opening heights (up to about 0.15H) the opening effect is relatively small in both spans (less than 10%). Increasing the opening height further, the deflections are significantly affected. The most significant effect is obtained when the opening is located at the composite girder center line (close to the interior support) or in zone 2. This may be attributed to the opening weakens the maximum shear stress zone in the first position, and the maximum positive bending moment zone (zone 2) in the second position. On the other hand, Figure 14 indicates the deflection behavior of continuous composite girder with rectangular opening in steel web at d=75cm, b =250cm and the distance between the edge of the opining and intermediate support = 200cm.
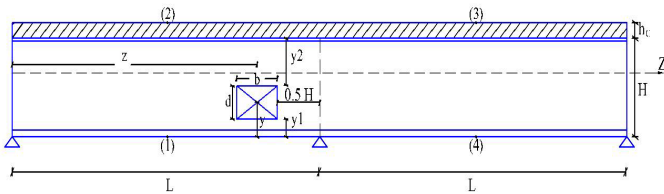
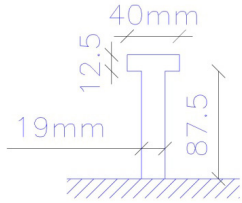**Figure 8**. Elevation of continuous composite girder with rectangular opening in steel web
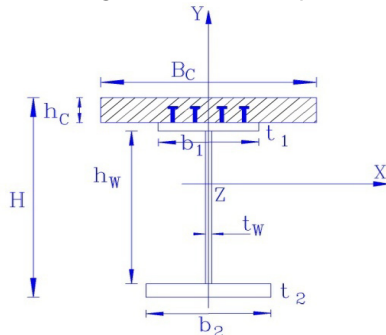

Figure (9-a). Stud shape

Figure (9-b). Girder cross-section

Table (2). Material properties for continuous composite girder

Concrete Slab		Steel Girder	
E_c (GPa)	f_c' (MPa)	E_s (GPa)	f_y (MPa)
34.30	30.00	214.00	370.00

Table (3). Dimension of cross-section for continuous composite girder (Refer to Figure 10-b for definitions)

Concrete Slab			
B_c (cm)	h_c (cm)	Top Mesh Reinf.	Bottom Mesh Reinf.
230.0	20.0	(6 Φ 12/m)	(6 Φ 16/m)

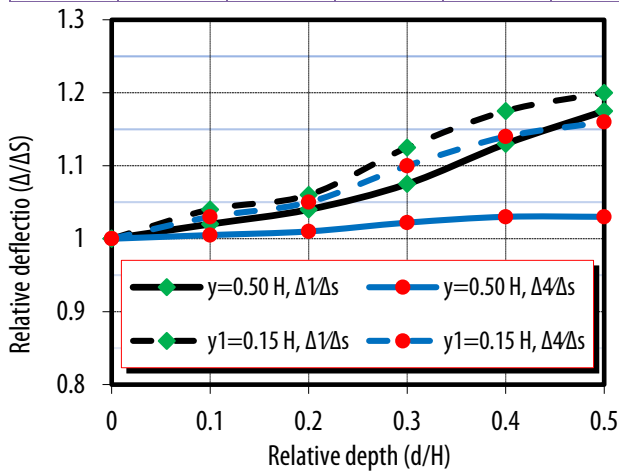| Steel Girder					
t_1 (mm)	b_1 (mm)	t_2 (mm)	b_2 (mm)	t_w (mm)	h_w (mm)
20.0	300.0	30.0	450.0	15.0	1550.0

Figure 10. Effect of opening height on the maximum deflections of the two spans for b= 0.10L (Opening to the left span)
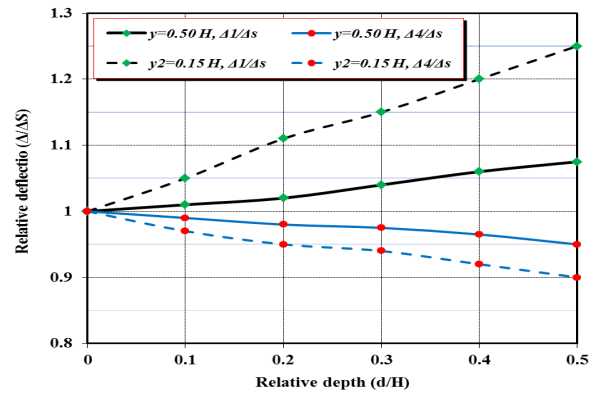

Figure 11. Effect of opening height on the maximum deflections of the two spans for b= 0.10L (Opening at the mid-span of left span)
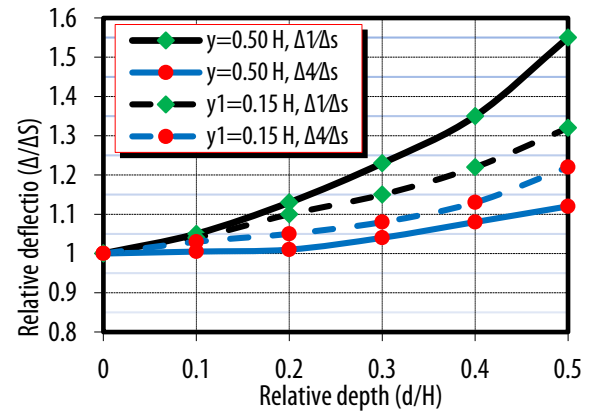

Figure 12 .Effect of opening height on the maximum deflection of the two spans for b= 0.15L (Opening to the left span)
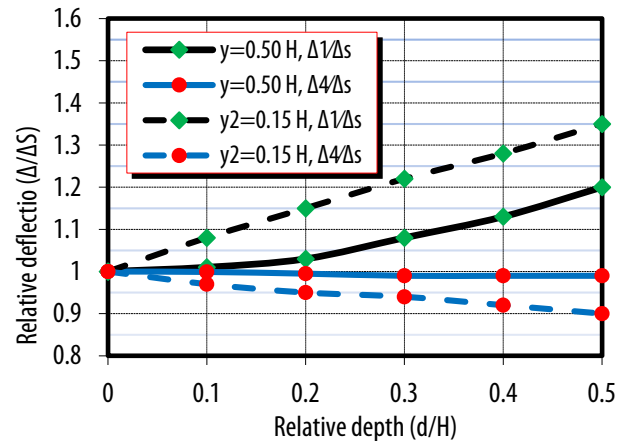

Figure 13. Effect of opening height on the maximum deflection of the two spans for b= 0.15L (Opening at the mid-span of left span)
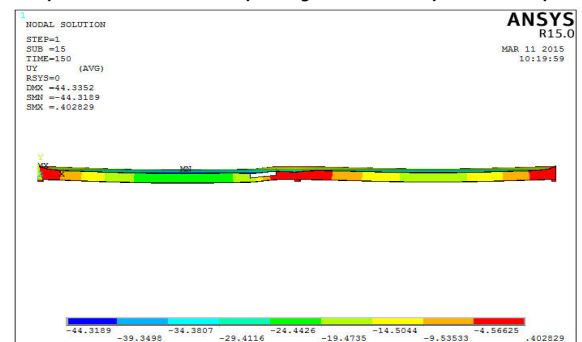

Figure 14. Deflection shape for two continuous composite girders with opining in the steel web

Effect of opening width on the relative vertical deflections

Figs. 15 and 16 show the effect of the opening width (d = 0.50 H) on the relative vertical deflections, (Δ1/Δs and Δ4/Δs) of the two spans. Figure 15 shows the case when the opening is positioned close to the interior support, while Figure 16 shows the case when the opening is positioned at the mid-span of the composite girder (in the compression zone and at the center line of the composite girder in both cases). From Figure 15, it can be noted that, increasing the opening width increases the deflections (Δ1 and Δ4) for both spans. The effect of opening width on the deflection is small for an opening width of less than 0.05L. As the opening width increases, the deflections significantly increase. The most significant effect of the opening width occurs when the opening is positioned at the composite girder center line. While positioning the opening at the mid-span caused dramatic changes in the deflection. From Figure 16 it can be seen that increasing the opening width increases the deflection Δ1 but decreases the deflection in the solid span Δ4. It was found that, for small opening widths (up to about 0.05L) the opening effect is relatively small in both spans (less than 10%). Whereas, increasing the opening width further has a significant effect on the deflection. This may be due to the variation in the span's inertia as a result of the opening. Comparing the effect of the height and width of the opening on the deflections of the spans, it can be noted that the opening width has a more significant effect than the opening height.
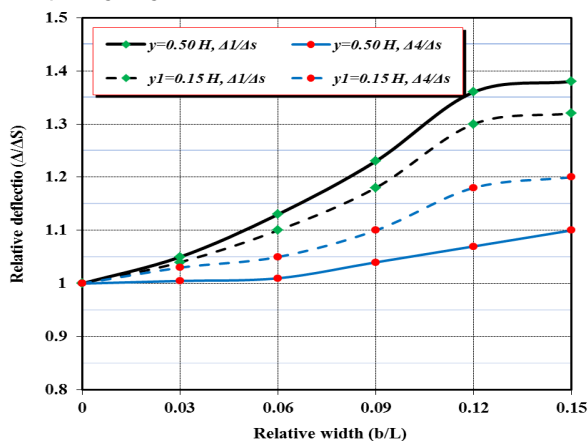

Figure 15. Effect of opening width on the maximum deflections of the two spans for d= 0.50H (Opening to the left span)
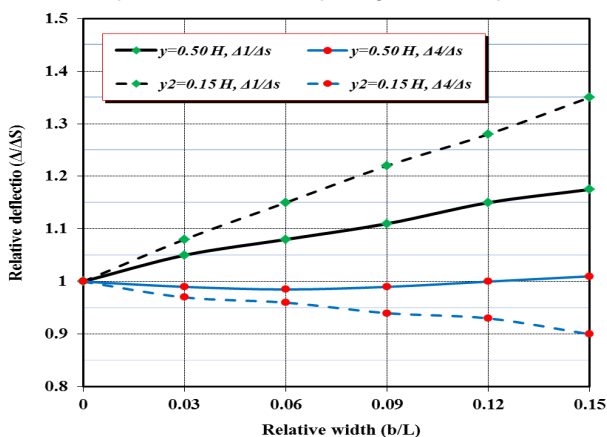

Figure 16. Effect of opening width on the maximum deflections of the two spans for d=0.50H (Opening at the mid-span of left span)

Effect of opening position along z-direction on the relative vertical deflections

To study the effect of the opening position along Z-direction, rectangular openings with constant dimensions (b=0.15L and d=0.50H) were analyzed. The value of Z-direction ranged from 0.10L to 0.90L. The opening was kept under the top fiber of the upper flange of the girder cross-section (Y2=0.15H).

Figure 17 shows the effect of the opening position along Z-direction on the relative vertical deflections of the two spans, (Δ1/Δs and Δ4/Δs). The results indicate that when the position of the opening is at the maximum shear zone close to the left support and in the maximum positive moment (Z up to 0.10L and Z ≈ 0.30 L to 0.50L) the deflection (Δ1) increases while the deflection (Δ4) decreases. When the position of the opening is at the zones where the moment and/or the shear stress are small, the deflection (Δ1) decreases whereas the deflection (Δ4) increases. Moreover, the results indicate that when the opening is moved towards the interior support (in the maximum negative moment), the deflections (Δ1) and (Δ4) increase.
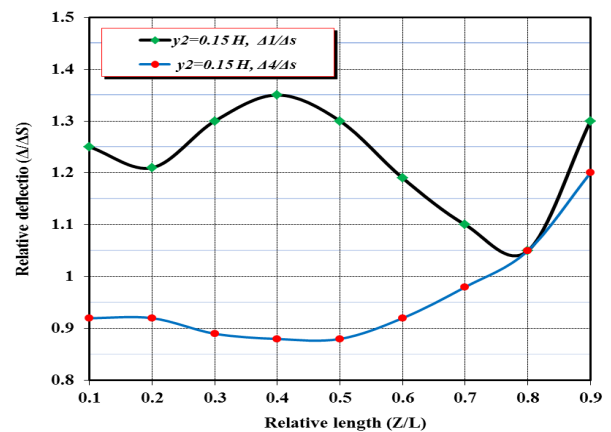

Figure 17. Effect of opening position along the girder span on the maximum deflections of the two spans for (y2 = 0.15 H) from the top fiber
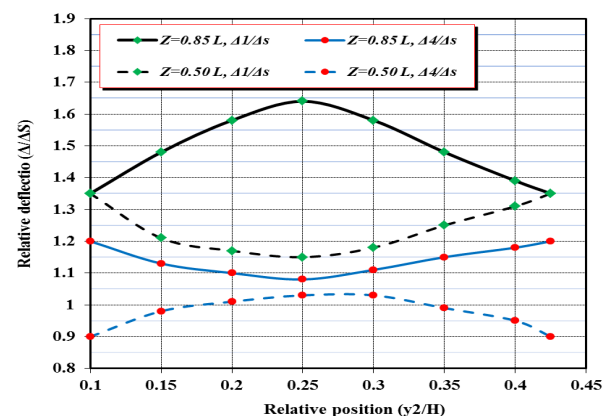

Figure 18. Effect of opening position along the girder height on the maximum deflections of the two spans for opening dimension of (d = 0.50 H) and (b = 0.15 L)

Effect of opening position along Y-direction on the relative vertical deflections

The opening position was studied along Y-direction at the left of the interior support and at the mid-span. It can be seen from Figure 18 that

when the opening was positioned to the left of the interior support the opening increases the deflections (Δ1 and Δ4) significantly and the most increase in deflection occurred when the opening was positioned in the maximum shear zone. Moreover, Figure 18 indicates that when the opening is positioned at the mid-span near the composite girder chords, the deflection (Δ1) increases while the deflection (Δ4) decreases. On the other hand, Figure 18 shows that when the opening is moved towards the composite girder center line, a reversible effect on the deflection of both spans is obtained.

Effect of opening height on the relative normal stress distribution for concrete slab

Figures 19 and 20 show the effect of opening height for b = 0.10L and 0.15L on the relative compressive stresses (σ2/σs, and σ3/σs for zones 2 and 3 respectively), when the opening is located at left of the interior support.

It can be seen that from Figs. 19 and 20 that increasing the opening height increases the compressive stresses for zones 2 and 3 especially when the opening is positioned in the intermediate steel web height. The most pronounced effect happened when the opening height exceeds 0.25H. This is due to increasing the opening height decreases the bottom chord height of the opening, which leads to a huge increase in the compressive stresses and consequently a local failure in this chord.

Figures 21 and 22 show the effect of opening height on the relative compressive stresses when the opening is located at the mid-span of left span. It can be seen from Figures 21 and 22 that increasing the opening height (for b = 0.10 L and 0.15L) decreases the compressive stresses (σ2) significantly. The most pronounced decrease obtained when the opening height ranged from 0.15H to 0.35H. This is due to the wide increase in the compressive stresses and consequently a local failure in the top chord of the opening. On the other hand, Figures 21 and 22 indicate that an increase in the opening height decreases the compressive stresses (σ3) up to 10% for the third zone. When the opening is positioned at the girder center line, an increase in the opening height increases (σ2) significantly and decreases (σ3). Figures 23 and 24 shows the stress distribution in the reinforced concrete slab in the area of intermediate support for two continuous composite girders and around the opening in steel web.
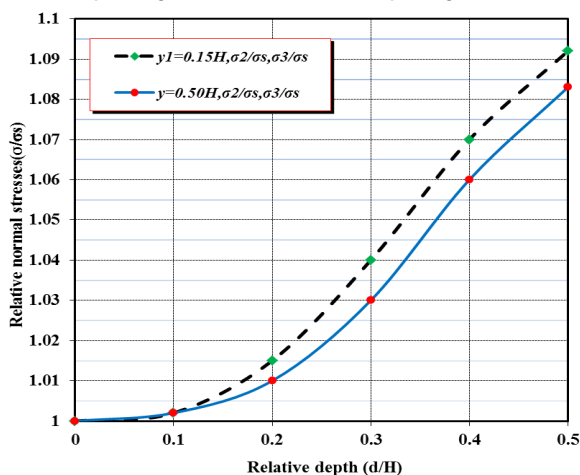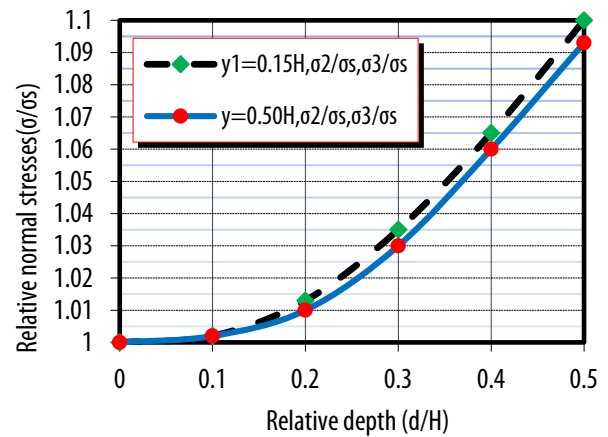

Figure 20. *Effect of opening height on the compressive stresses of the two spans for b= 0.15L Opening to the left span*

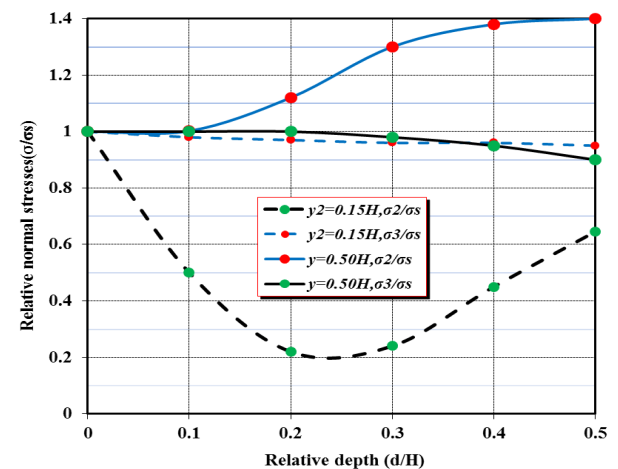***Figure 21***. *Effect of opening height on the compressive stresses of the two spans for b= 0.10L Opening at the mid-span of left span*
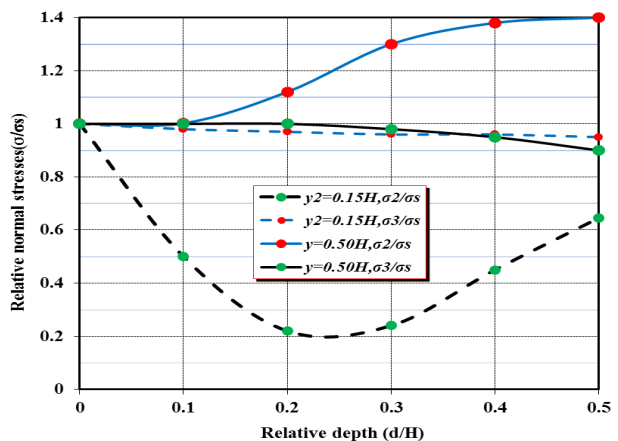

Figure 22. *Effect of opening height on the compressive stresses of the two spans for b= 0.15L Opening at the mid-span of left span*

At the ends of the left and right supports to a point of zero bending moment in the composite section, the concrete slab is compressed as shown in Figure 23. While at the distant between the two points of zero bending moment above the intermediate support the concrete slab is tensioned and the concrete in this zone suffers from cracks as shown in Figure 24. On the other hand, Figure 25 shows the stress distribution in the steel web around the opining for two continuous composite girders. It can be seen that the stresses at corner of opening have the maximum values.
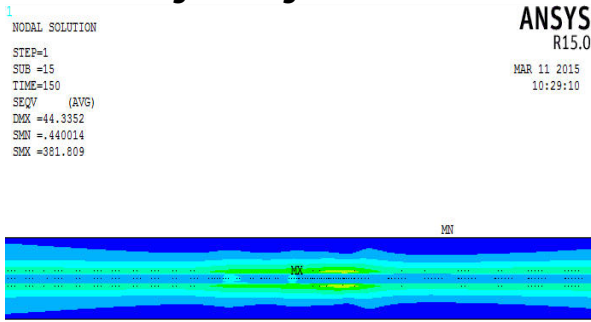

Figure 19. *Effect of opening height on the compressive stresses of the two spans for b=0.10L Opening to the left span*

Figure 23. *Stress distribution in the reinforced concrete slab in the area upper intermediate support for two continuous composite girders*
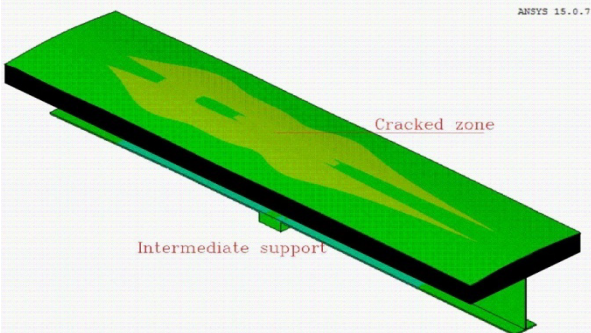

Figure 24. *Cracked zone in the reinforced concrete slab upper intermediate support for two continuous composite girders*
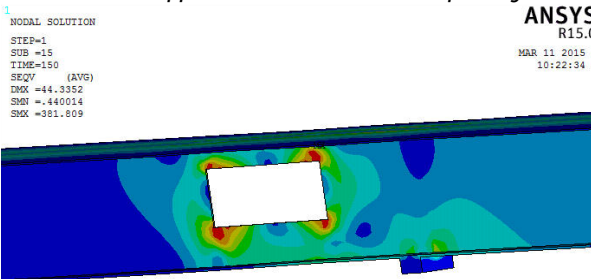

Figure 25. *Stress distribution in the steel web around the opining for two continuous composite girders*

Effect of opening width on the normal stress distribution for concrete slab

Figures 26, and 27 show the effect of the opening width (d=0.50H) on the relative compressive stresses. When the opening is positioned to the left of the interior support (in zone 3 and at the composite girder center line), the stresses (σ2 and σ3) increase with an increase in the opening width (Figure 26). The opening width effect is similar on both σ2 and σ3. The most pronounced effect in the stress distribution (σ2 and σ3) is explicitly noted when the opening is positioned at the intermediate support. When the opening is positioned at mid-span, it is found that the stresses (σ2) are highly affected by the increase in the opening height either when the opening is positioned in the compression zone (zone 2) or at the composite girder center line (Figure 27). This shows the opening effect on the stress distribution. Moreover, Figure 27 shows that when the opening is positioned in zone 2, the stresses (σ3) decrease with the increase in opening height, while a negligible effect on (σ3) is obtained when the opening is positioned at the girder center line.
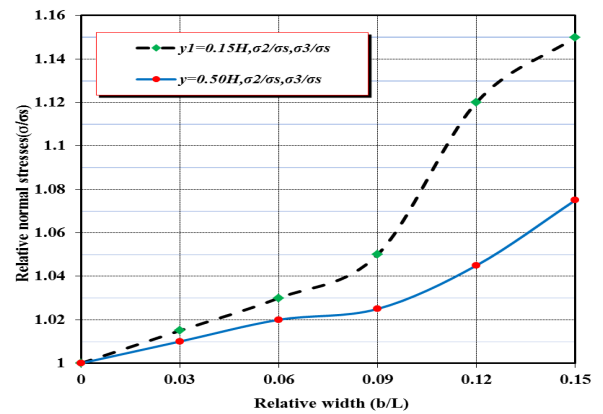

Figure 26 . *Effect of opening width on the maximum compressive stresses of the two spans for d=0.50H Opening to the left span*
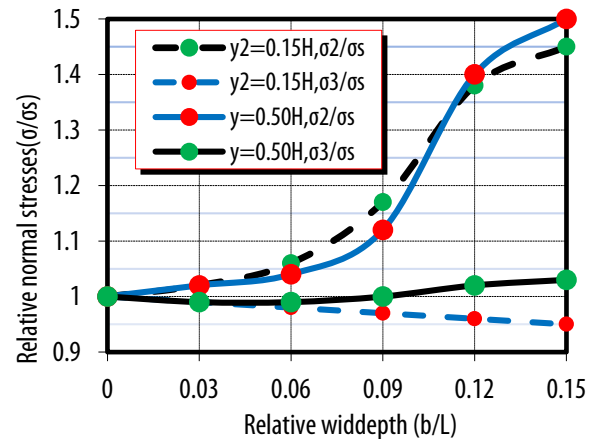

Figure 27. *Effect of opening width on the maximum compressive stresses of the two spans for d=0.50H Opening at the mid-span of left span*

Effect of opening position on the normal stress distribution

To study the effect of opening position on the continuous composite girder stress distribution, two values namely Z= 0.5L and Z= 0.85L were selected along the depth of steel section (H) with opening size b=0.15L and d=0.50H.
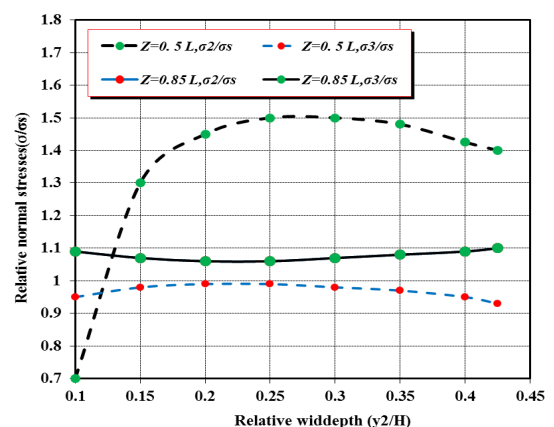

Figure 28. *Effect of opening position along the girder depth on the maximum compressive stresses of the two spans for opening dimension of (d = 0.50H) and (b = 0.15L)*

Figure 28 shows the effect of the opening position on the σ2 and σ3. It can be seen that when the opening position changes along the depth (H) to the left of the interior support, both σ2 and σ3 increase similarly. The

maximum value obtained when the opening is located close to the top and bottom fibers for the composite girder cross section. At the mid-span, when the opening is positioned close to the top and bottom fibers of the composite girder, the σ_3 decreases, while negligible changes are obtained when the opening moves toward the section center line. At the same time, σ_2 decreases significantly when the opening is located in zone (2). When the opening moves away from the top flange of the composite girder, the stresses (σ_2) increase. This indicates the effect of stress concentrations around openings at these positions.

CONCLUSIONS

Non-linear finite element model used in this study was able to simulate the behavior of deflection in the steel section and internal stresses in the concrete slab for continuous composite girders with rectangular opening in the steel web. The results indicated that when the width of opening less than 0.05 of the length of single span and the height less than 0.15 of steel web, the deflection and internal stresses in the concrete slab increased less than 10 % comparing to continuous composite girders without opening. Moreover, the results showed that the position of opening must be located in the zones with very small internal stresses.

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