Torsional Resistance of Reinforced Concrete Girders with Web Openings

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ABSTRACT

In this study, a three dimensional finite element analysis was utilized to study the behavior of reinforced concrete T-girders with and without web openings under pure torsion by using ANSYS APDL 15.0 program. Fourteen reinforce concrete T- girders were analyzed; one of the girders (without web openings) was modeled as a control girder. The analysis variables considered for the other girders are: size, shape, position of web openings, number of web openings and the method was used to strengthen the member at openings, (using internal deformed steel bars as in the case where the openings are planned before casting the girders). To study the general behavior of finite element models, torque-angle of twist plots at the end of the span near the loaded arms were represented. From this relation, it was showed a decreasing in the strength of the T-girders with web openings under the torsional loads and increasing of the angle of twist. The results were analyzed in terms of torque twist characteristics; ultimate torque, crack patterns, crack width, warping and stresses. These terms were presented and a comparison between the finite element results was made.

Keywords: finite element analysis, torsion, reinforced concrete, web opening, girder.

مقاومة اللي للأعتاب الخرسانية المسلحة حاوية على فتحات وترة

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الخلاصة

تم من خلال هذا البحث دراسة سلوك العتبات الخرسانية المسلحة لعتبات بشكل T الحاوية على فتحات وعتبات بدون فتحات تحت تأثير عزم اللي الصرف ;تمت نمذجة العتبات بأستخدام طريقة العناصر المحددة لنماذج ذات ابعاد ثلاثية بأستخدام برنامج ANSYS APDL 15.0، حيث تم تحليل اربعة عشر نموذج احدها بدون فتحه والذي يعتبر النموذج المصدري حيث تم مقارنة نتائج بقية النماذج معه. المتغيرات التي تم استخدامها عند دراسة المقارنة مع االنماذج الأخرى هي: حجم وشكل وموقع وعدد الفتحات المستخدمة وطريقة تقوية الفتحات التي تتم بأستخدام تسليح داخلي حول الفتحات عند التصميم. ولأجل دراسة العلاقات المتعلقة بالنماذج والمصممة بطريقة العناصر المحددة, كالعلاقة بين عزم اللي الصرف وزاوية الألتواء والتي تم قياسها عند نهاية مقطع العتبة القريبة من الذراع الذي يسلط عليه الأحمال, وبشكل عام ومن خلال هذة الدراسة وجد تناقص في مقاومة العتبات لعزوم اللي الصرف وزيادة في مقدار زاوية عزم الألتواء عند وجود الفتحات .و تمت ايضا دراسة نتائج حساب اقصى عزم التواء وشكل وسمك التشققات ودراسة الأنحناءات والأجهادات وتم اجراء مقارنة فيما بينها.

كلمات المفتاح:العناصر المحددة, عزم الألتواء, الخرسانة المسلحة, الفتحات, العتبات.

1. INTRODUCTION

In current buildings construction, a transverse opening in reinforced concrete (RC) beam is often presented for the passage of utility pipes and ducts. These pipes or ducts are requisite to accommodate with fundamental services such as air-conditionings, electricity, water supplies, computer networks, and telephone wires, **Ahmed, et al., 2012**. The passing of these ducts through the openings in the RC floor beams eliminates a significant amount of dead space and results in a more economical and compact design, **AL-Shaarbaf, et al., 2007**.

The effects of an opening on the RC beam behavior and strength must be considered; including transverse openings in the web of a RC beam induces high stress concentration at opening corners, alters the simple beam behavior to a more complex one and reduces beam stiffness. While providing a large opening, the effects on service and ultimate load behaviors of the beam must be properly accounted for in the design, **AL-Shaarbaf, et al., 2007**. An opening in a RC beam creates discontinuity in the stresses normal flow, this leads to early cracking of concrete due to stress concentration at edges of the opening. To avoid this, special reinforcement enclosing the opening should be provided in the form of internal or external reinforcement. Internal reinforcements are steel bars provided along with the main reinforcements during casting. External reinforcements are applied externally around opening in the form of jacketing of composite materials like glass fiber or carbon fiber reinforced polymer called GFRP or CFRP, **Venugopal, 2014.**

2. BACKGROUND

Daniel and McMullen, 1977, presented in their paper a method for predicting the torsional strength of a concrete beam that contains an opening and is reinforced both longitudinal and transversely. Sixteen beams were tested of which two did not have an opening (solid beams). The other beams contained an opening that was placed symmetrically except in B47 and B48 with unsymmetrically position of opening. All specimens were subjected to pure torque at their solid ends. The load was applied in increments and after the application of each increment of load, the strains, rotations, and deflections were recorded and the cracks were marked.

McMullen and Daniel, 1975, displayed equations for predicting the torsional strength of RC beams that contain openings to be used as service ducts. The results were compared with the test results of 29 concrete beams. The strength of beams containing a small opening can be larger than the strength predicted by the theory because the spiral crack extends into the solid portion of the reinforced concrete beam. Although, all the tested beams were subjected to pure torsion, the analysis includes the moment and the shear due to self weight of the RC beam and thus can easily be outspread to include members supporting external loads that cause bending and shear.

Venugopal, 2014, tested eleven beams of the same dimensions. Beams were divided into two series. The first series was cast with circular opening whereas the second was cast with rectangular openings of the same cross sectional area. One beam without web openings was also casted and treated as control beam. Each series consisted of five beams; the first beam had a centrally located single opening and the remaining four were cast with two symmetrically located openings. The other three beams with two openings of both series were retrofitted with bi-directional GFRP fabric.

Fawzy et al, 2014, studied the use of externally bonded fiber reinforced polymers to strengthen concrete beams with a large web opening subjected to pure torsion. An experimental work was carried out to investigate the torsional behavior up to failure of nine RC beams having the same dimensions and reinforcement. One of them is solid without opening as a reference beam and one of the remaining eight beams was tested without any strengthening and seven beams were strengthened with carbon fiber reinforced polymer (CFRP) with different schemes. The major parameter included in this study was the strengthening effect of different schemes of CFRP sheets on behavior of RC beams with a large web opening under pure torsion.

3. OBJECTIVE

The research investigation aimed to study the behavior and strength of a reinforced concrete T-girder with and without a web opening under pure torsion, using ANSYS APDL 15.0 Program. The major variables of the study were the number, size, shape, position of web openings along the span and the reinforcement around openings. During the static analysis, the variables measured for each T-girder were torque versus angle of twist values at the free end of the girder near the loading arm on both concrete and steel, crack pattern, crack width, warping and stresses.

4. VERIFICATION OF THE FINITE ELEMENT IDEALIZATION

The validity and accuracy of finite element idealization were studied and checked by analyzing reinforced concrete beam (B1) that tested experimentally by **Mansur et al. 1983a** as shown in **Fig.1b**. The aim of the comparison is to ensure that the elements, material properties and convergence criteria are adequate to model the response of the beams and to be sure that the simulation process is correct. The concrete beam was modeled using 8-node brick elements (Solid 65). The reinforcing bars were modeled using 2-node element (Link 180). The loading arm and the steel plates were modeled using (Solid 45) elements, as shown in **Fig.1a**. Due to the nature of the torsional problem, where there are out-of-plane as well as in-plane forces, the model is generated with mainly three dimensional elements. A square or rectangular mesh is recommended and the total number of nodes equals 3223 while the total number of elements equals 3615. The shear transfer coefficients for closed and open cracks of values 0.6 and 0.7, respectively after several of trails. Convergence criteria was set as (U = 0.05) and the Norm was infinite.

4.1. RESULTS OF FINITE ELEMENT VERIFICATION MODEL

Fig.2 represents the relationship between the torque and the angle of twist, and revealed that the general behavior for the tested beams in torsion is well established by the adopted numerical model. The analytical results show that the prediction of the ultimate torque capacity of the beam was close to the experimental result; while the prediction of angle of twist was smaller than the experimental result by 24%.

5. FINITE ELEMENT IDEALIZATION OF THE T-GIRDER

The (Solid65) element was used to model the concrete and (Link180) element was used to model steel reinforcement, while the (Solid45) element is used for modeling the steel plates at the supports and steel arms. Fourteen reinforced concrete T-girders were modeled, details are given in **Table 1**. The (Solid65) element requires linear isotropic and multi-linear isotropic material properties to properly model concrete. The modulus of elasticity of the concrete, (EX = 23500 MPa) and Poisson's ratio is taken as (0.2). The uniaxial cracking stress is based upon the modulus of rupture which was (f_r =3.1). The uniaxial crushing stress in this model was based on the uniaxial unconfined compressive strength ($f_{c'}$= 25 MPa). For the (Link180) element, the bilinear model requires the yield stress (f_y = 400 MPa) for longitudinal and stirrups reinforcement, as well as the hardening modulus of steel to be defined as zero. Elastic modulus is defined as (EX = 200000 MPa) and Poisson's ratio PRXY as (0.3). For the (Solid45) element, the element was modeled as a linear isotropic element with a modulus of elasticity for the steel as (EX =200000 MPa) and Poisson's ratio PRXY as (0.3).

5.1 Dimensions and Details of T-Girder

Dimensions of the tested T- Girders are: length of girder is 20000 mm, width of flange is 1000 mm, thickness of flange is 200 mm, width of web is 400 mm and depth of web is 1200 mm. A concrete cover of 40 mm was used in the web of the T-girder and 25 mm in the flange, see **Fig.3**. Dimensions of the steel arms are (500×200×500) mm from the flange, (500×1200×800) mm from the web and for the steel plates are (500×50×400) mm. Diameter of circular openings is 400 mm and 600 mm which equals about % 33.3 and % 50 of the depth of web; the depth of the rectangular and square web openings was % 33.3 and % 30 of the depth of web. The T-girders were reinforced with 9Ø36 mm deformed bars as flexural reinforcement. The shear reinforcement (stirrups) was Ø12 mm deformed bars at 250 mm c/c. Bars of Ø12 mm deformed bars at 500 mm c/c were used as horizontal and longitudinal reinforcements for the flange of the T-girder. This reinforcement was used for all T-girders that were with unstrengthened openings except girder (G8) and (G13). T-girder (G8) was strengthened with pre-fabricated internal deformed steel bars (additional reinforcements around opening) consisting of 8Ø12 mm diagonal bars around the openings, 4Ø12 mm horizontal bars above and below the openings and concentrated stirrups Ø12 mm above and below the opening at 50 mm c/c. The additional reinforcement for (G13) increased near the opening greater than the additional reinforcement in (G8). **Fig.4** shows model of the specimens. The shear transfer coefficients for open and closed cracks of values 0.3 and 0.5, respectively. Convergence criteria were set as default and the Norm was L2.

5.2 Modeling of the T-Girder

Full T-girders were used in modeling with proper boundary conditions. The concrete, steel plates and steel arms of the T-girders were modeled as volumes. It should be noted that for specimens

(CG, G1 to G13), some modification of dimensions was made due to geometric constraints from the some elements in the models, i.e. meshing of concrete elements and steel rebar locations.

5.3 Meshing of the T-Girder

The use of a square or rectangular mesh is recommended to obtain good results from the Solid65 element, **Jindal, 2012**, and **Wolanski, 2004**, and using a tetrahedron mesh around the web openings as shown in **Fig.5** except T-girder (G3), (G8) and (G13), using a square or rectangular mesh for all. No mesh of the steel reinforcement is needed because individual elements were created in the modeling through the nodes created by the mesh of the concrete volumes as shown in **Fig.7**. The command 'merge items' is used to merge separate entities that have the same location.

5.4 Loading and Boundary Conditions

The analyzed T-girder was supported at a distance of 1.0 m from the ends on cylindrical bearings. These bearings permitted free torsional rotation at the supports as shown in **Fig.6**. A loading arm was attached to the T-girder at each support. The load was applied to one of the loading arms while the other loading arm was held in position in ux, uy, uz directions. The ultimate torsional strength for the control girder was 163.5025 kN.m.

5.5 Parametric Study

In order to investigate the effects of most important parameters affecting the torsional capacity of RC T-girders with web openings, a parametric study have been carried out in this study, these parameters include:

1- Shape of the openings.
2- Size of the openings.
3- Number of the openings.
4- Position of the openings.
5- Strengthen of the openings.

5.6 Results and Discussion

The general relationship between torque and angle of twist is such that, initially linear elastic behavior at a low loading stage was observed, the load gradually increased up to failure. Finite element analysis, using ANSYS program, was used to simulate concrete T-girders with and without single and multiple web openings. The general behaviors of the modeled girders were represented by the torque-angle of twist plots at the end of the span near the loaded arms showed a decreasing in the ultimate torsional strength of the T-girders due to introducing openings in the web, using the same longitudinal and transverse reinforcements except T-girders (G8) and (G13) as shown in **Fig.9** to **Fig.21.**

It has been found for T-girder which casted from ordinary concrete, when the diameter of opening increased, the reduction of ultimate strength increased and the pattern of cracking, as well as mode of failure of the T-girder changed. The depth of the opening with 30%, 33.3% and

50% of the overall depth of the web of the T-girder had an effect on decreasing the ultimate torsional strength of the T-girder and the depth of web opening had a greater effect than the effect of the length of web openings.

Concerning the effect of the shape of the web openings, it was found that there was difference between circular, square and rectangular web openings, the effect of square and rectangular web openings were decreasing the ultimate torsional strength greater than the circular web openings.

The location of the web opening in the center of the web of the T-girder has a larger effect than the position near the end of the T-girder span. The changing of the eccentricity of the web openings showed a decreasing in the ultimate torsional strength of the T-girders for (G7) with % 3.31, while the eccentricity of the web openings showed a decreasing in the ultimate torsional strength of the T-girders for (G9) with % 6.92. This shows that the effect of the eccentricity of the web opening near the flange was less than the effect of the eccentricity of the web opening near the bottom of the web; the flange of T-girder elements loaded with pure torsional had a beneficial effect on their load capacity. The eccentricity of the web opening at the center of the T-girder (G1) has a decreasing of % 3.980 of the ultimate torsional strength.

The number of web openings reduced the torsional strength as it increased. The reduction in ultimate torsional load of (G1) with one circular opening was % 3.980 while for (G5 and G11) with two circular openings was % 5.693 and % 7.868, respectively. For (G12) with four circular openings, the reduction in ultimate torsional load was % 5.000. The different between the results of the above T-Girders was the effect of position of web openings besides the effect of the number of web openings.

The application of strengthening arrangement presented in this research for T-girder (G8) and (G13) with square web opening had an effect on the T-girder deflection, controls cracks around openings, and decreased the ultimate capacities of the girder by about % 7.657 and % 1.440, respectively.

The warping for T-girder without web openings was less than warping of the T-girder with web opening at some position and was greater at other position while the warping near the opening was greater than the warping near the loaded arms. The angle of twist was increased when there was a web opening.

The crack first appeared with spiral view near the opening with an angle of 45° and then extended to the top of the flange and for the entire web of the T-girder with the same angle; the extended cracks greatly increased in the beginning near the bottom of the web than the top of the flange. In general, torsional cracks occurred early at mid span for control T-girder, and at the opening for other T-girders. Increasing the applied loads induced additional diagonal torsional cracks. The crack width increased as the size, number of opening, eccentricity and strength of openings increased.

The maximum stresses appeared around the openings and the lowest stresses appeared at the end of the T-girder. **Fig.8** shows the deformed shape of the control girder CG. **Fig.22** and **Fig.23** show the numerical crack patterns and the numerical XY-shear stress, respectively. **Fig.24** shows the numerical stress intensity of the reinforced concrete for (G13) and **Table 2** shows the summary of numerical torque results.

5.7. Conclusions

Conclusions drawn from the theoretical work are summarized as follows:

1- The general behaviors of the modeled girders were represented by the torque-angle of twist plots at the end of the span near the loaded arms showed a decreasing in the ultimate torsional strength of the T-girders. The depth of web opening had a greater effect than the effect of the length of web openings.

2- Concerning the effect of the shape of the web openings, it was found that there was difference between circular, square and rectangular web openings, the effect of square and rectangular web openings were decreasing the ultimate torsional strength greater than the circular web openings.

3- The location of the web opening in the center of the web of the T-girder has a larger effect than the position near the end of the T-girder span. The changing of the eccentricity of the web openings showed a degreasing in the ultimate torsional strength of the T-girders. The effect of the eccentricity of the web opening near the flange was less than the effect of the eccentricity of the web opening near the bottom of the web.

4- The number of web openings reduced the torsional strength as it increased.

5- The application of strengthening arrangement around web opening had an effect on deflection, controls cracks around openings and on decreasing the ultimate torsional capacity of the T-girder.

6- The warping for T- girder without web openings was less than warping of the T-girder with web opening at some position and was greater at other position while the warping near the opening was greater than the warping near the loaded arms.

7- The angle of twist was increased when there was a web opening.

8- The crack first appeared with spiral view near the opening with an angle of 45° and then extended to the top of the flange and for the entire web of the girder with the same angle; the extended cracks greatly increased in the beginning near the bottom of the web than the top of the flange. In general, torsional cracks occurred early at mid span for control T-girder, and at the opening for other T-girders. The crack width increased as the size, number of opening, eccentricity and strength of openings increased.

9- The maximum stresses appeared around the openings and the lowest stresses appeared at the end of the T-girder.

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Symbols and Abbreviations

E	modulus of elasticity of the material.
f	stress at any strain ε.
f_c'	cylinder compressive strength of concrete, MPa.
f_r	modulus of rupture.
f_y	yield stress of tensile reinforcement.
ANSYS	analysis Systems (Software).
APDL	ANSYS parametric design language.
CFRP	carbon fiber reinforced polymer composites.
FEM	finite element method.
GFRP	glass fiber reinforced polymer composites.
RC	reinforced concrete.
υ	poisson's ratio.
ɵ	angle of twist from torsion.

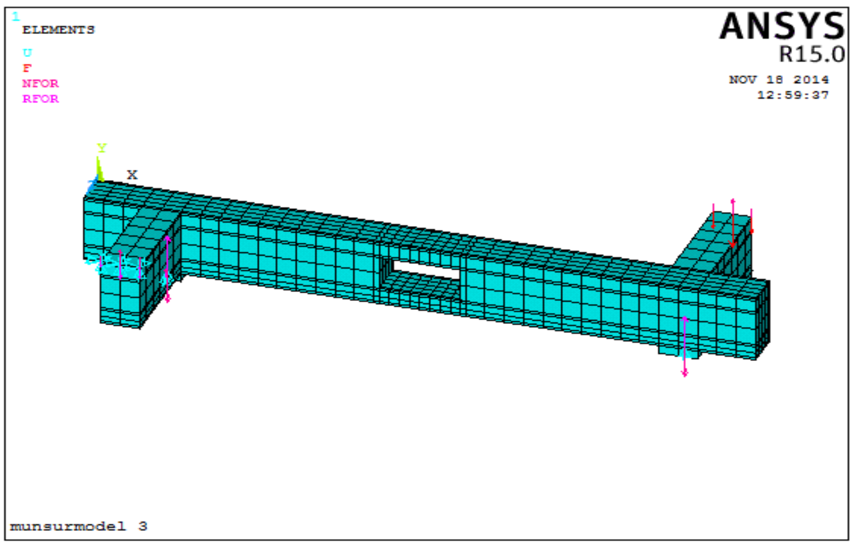


Figure 1a.FE idealization of the beam B1.

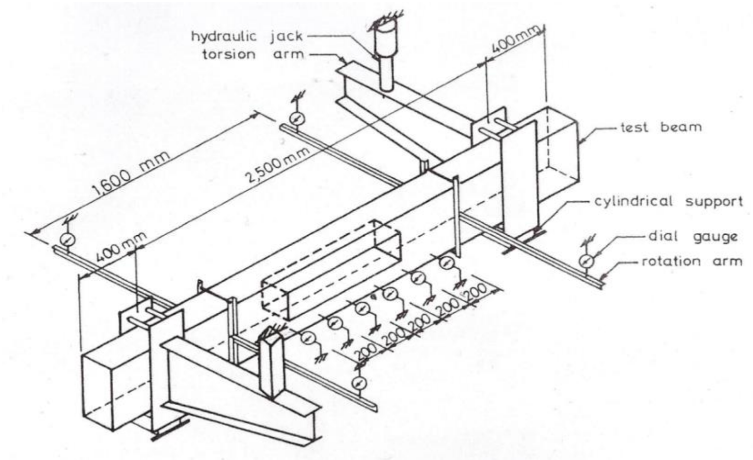


Figure 1b. Test set up and instrumentation of B1.

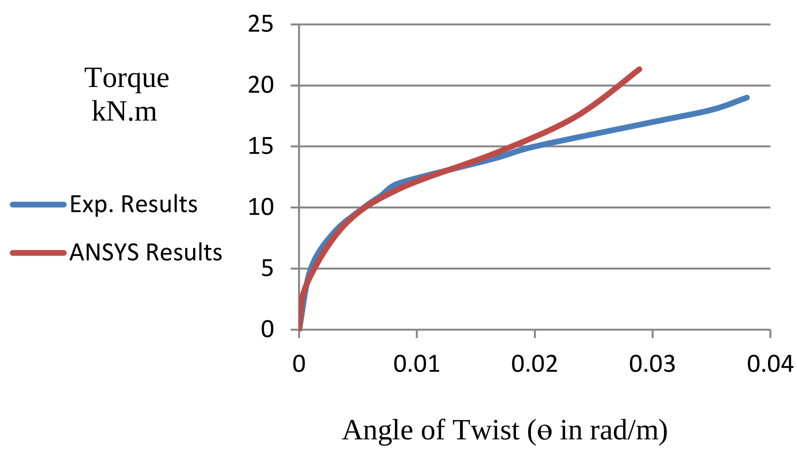


Figure 2. Numerical torque-twist behavior for beam B1.

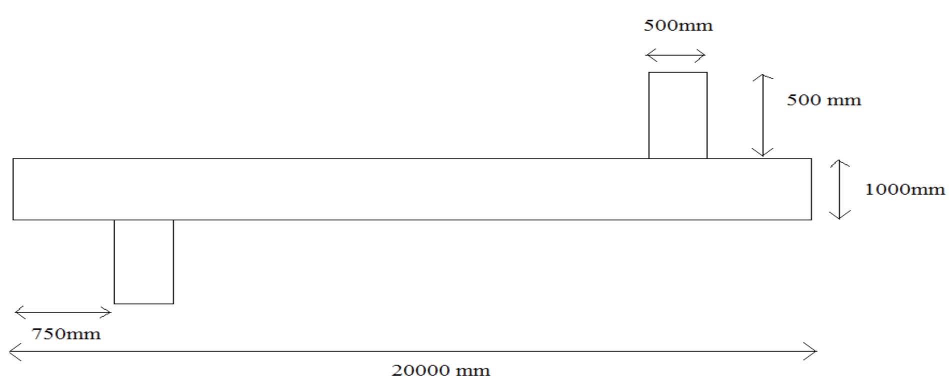
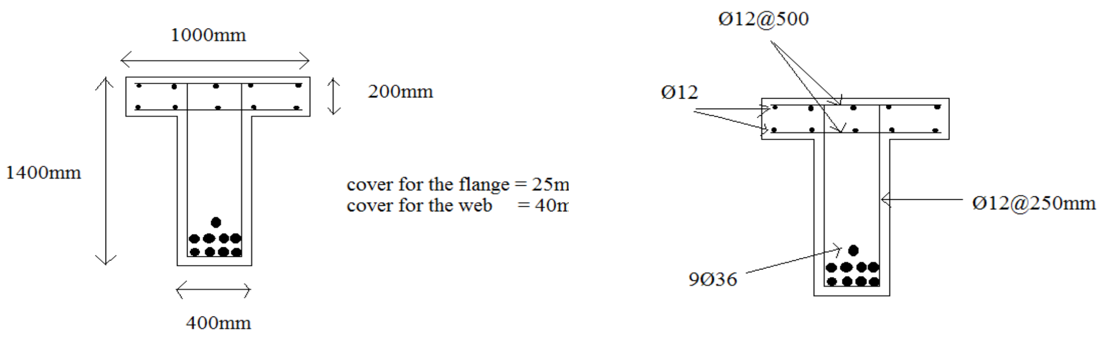


Figure 3a. Top view of the control girder model.



b.Steel reinforcement layout of the control T-girder.

Figure 3. Dimensions and steel reinforcement layout of the control T-girder.

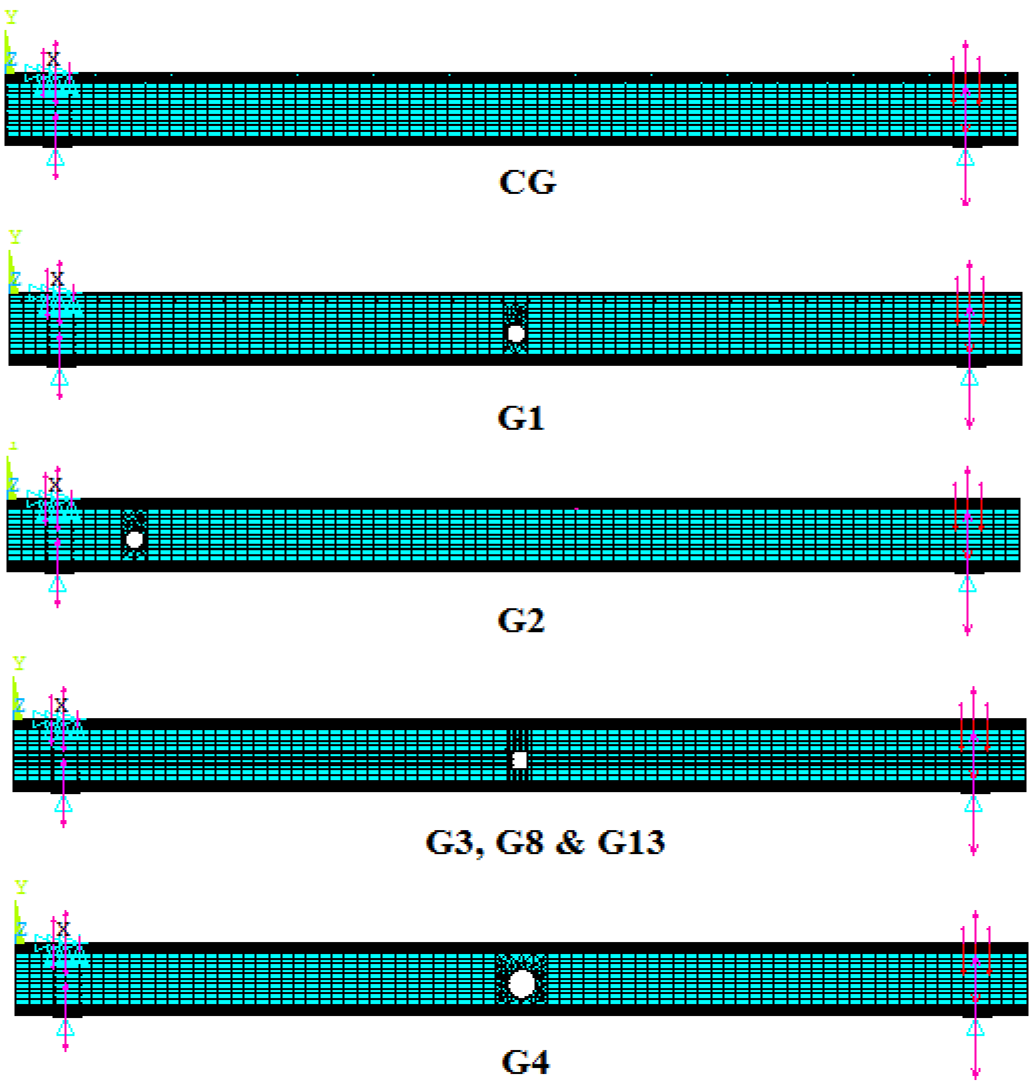


Figure 4a. Model program, from CG to G4, G8 and G13.

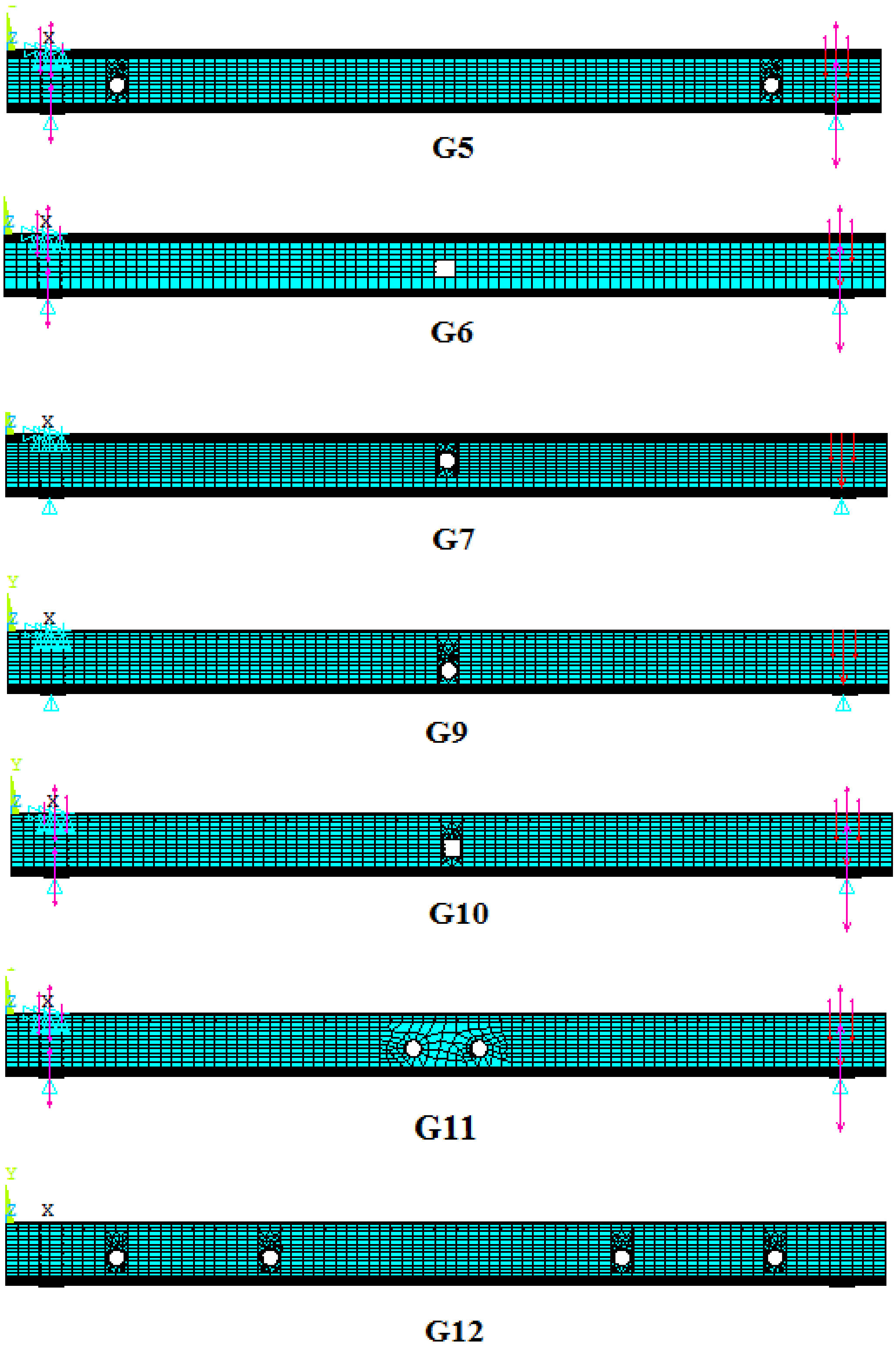


Figure 4b. Model program G5, G6, G7 and from G9 to G12.

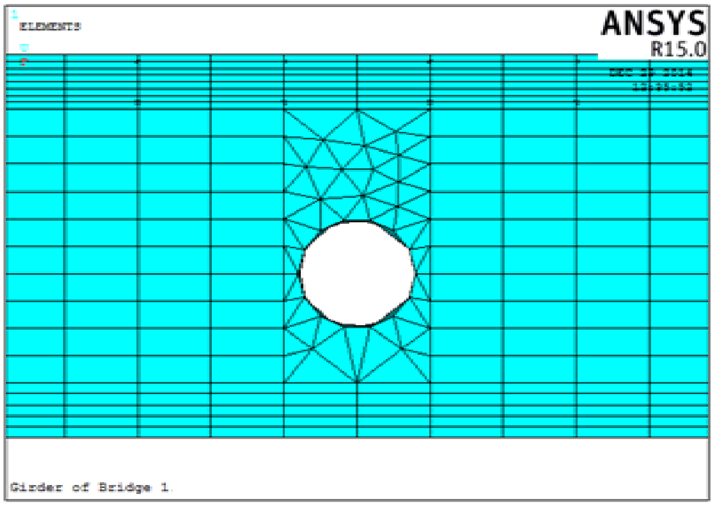


Figure 5. Square or rectangular and tetrahedron mesh were used.

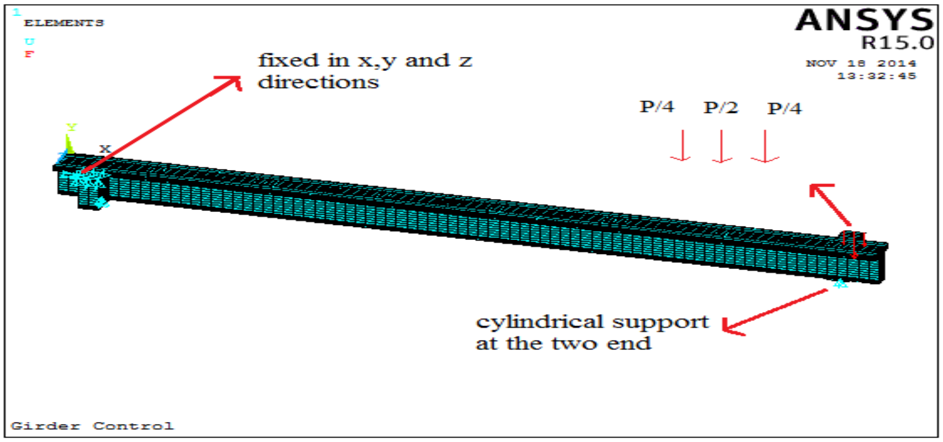


Figure 6. Loading and boundary conditions of CG used in the analysis.

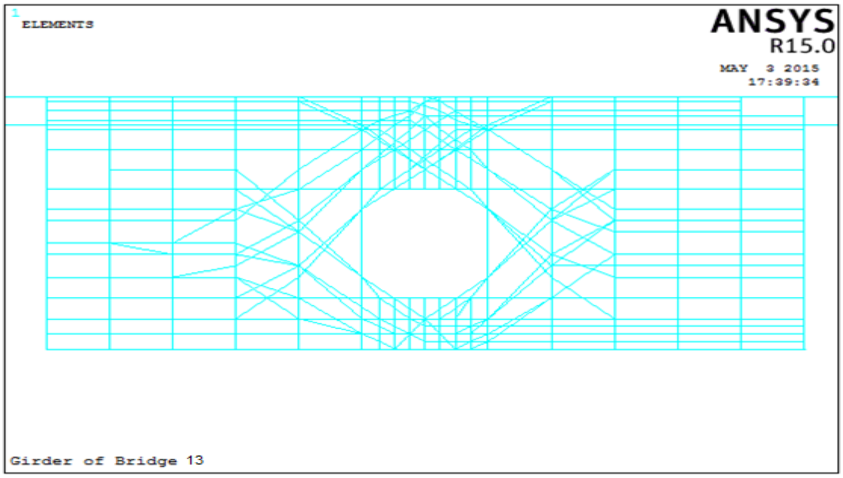


Figure 7. Additional reinforcement of T-girder G13.

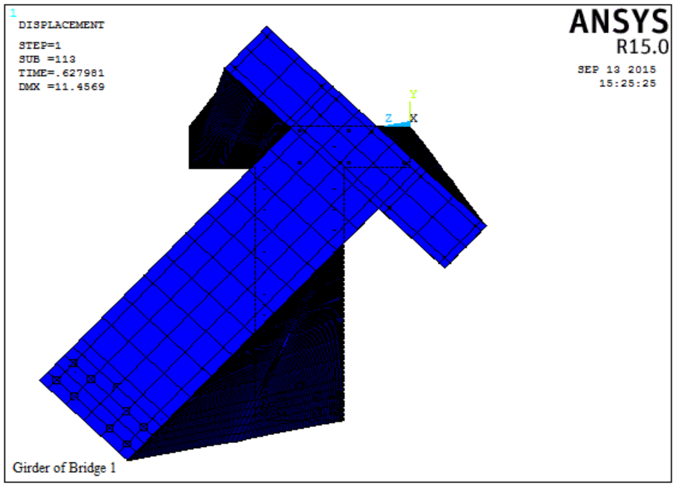


Figure 8. The deformed shape of the control girder CG.

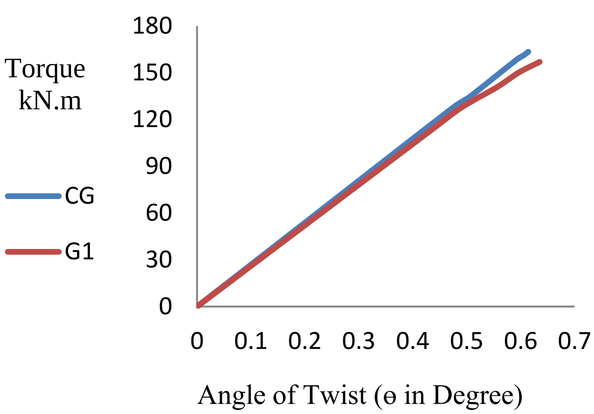


Figure 9. Torque-twist behavior for G1.

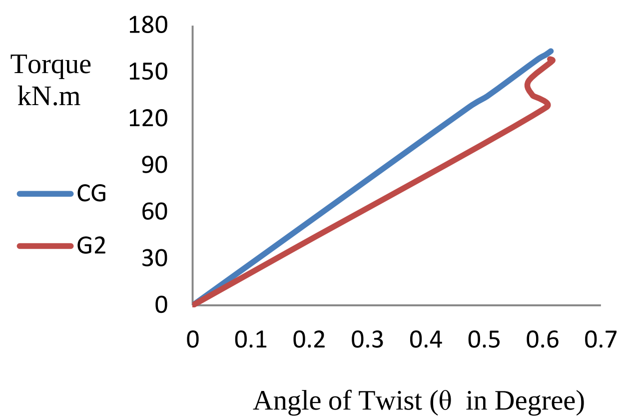


Figure 10. Torque-twist behavior for G2.

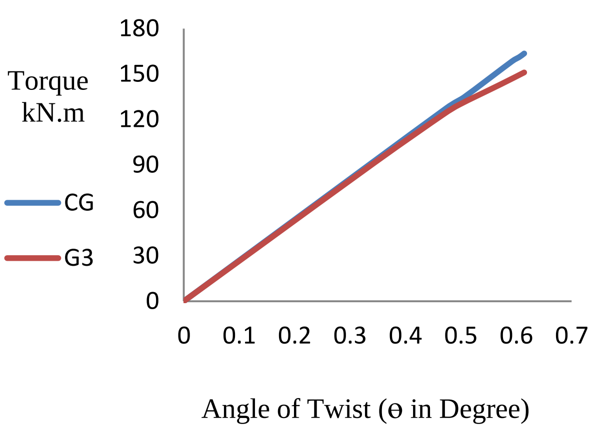


Figure 11. Torque-twist behavior for G3.

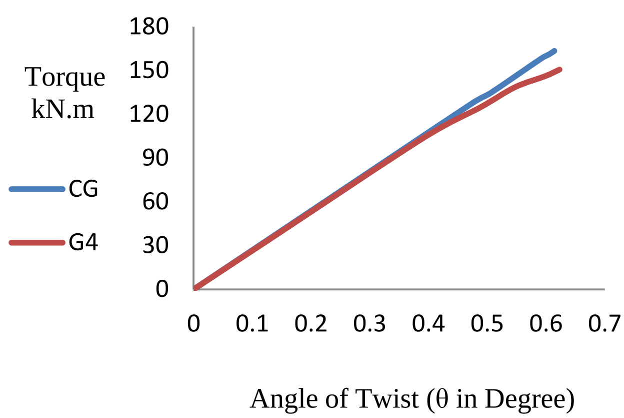


Figure 12. Torque-twist behavior for G4.

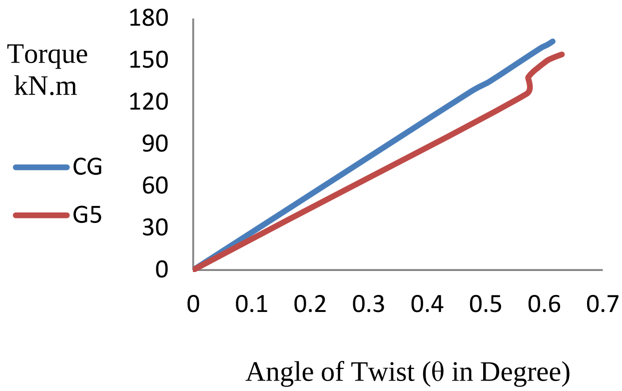


Figure 13. Torque-twist behavior for G5.

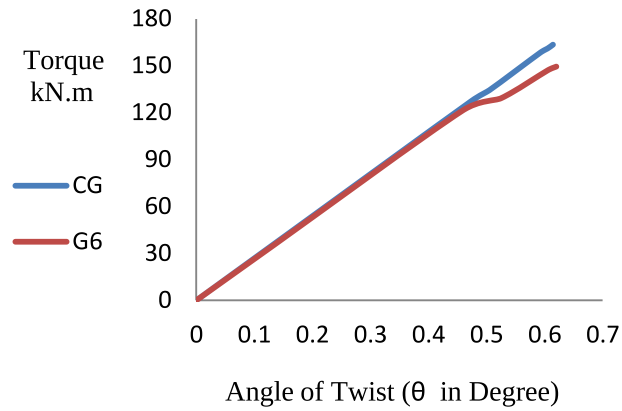


Figure 14. Torque-twist behavior for G6.

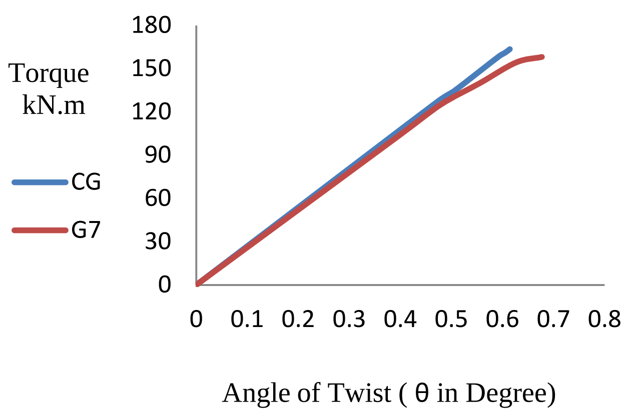


Figure 15. Torque-twist behavior for G7

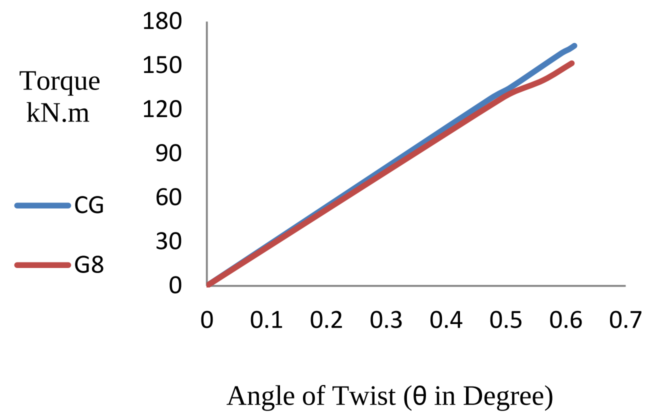


Figure 16. Torque-twist behavior for G8**.**

Figure 17. Torque-twist behavior for G9.

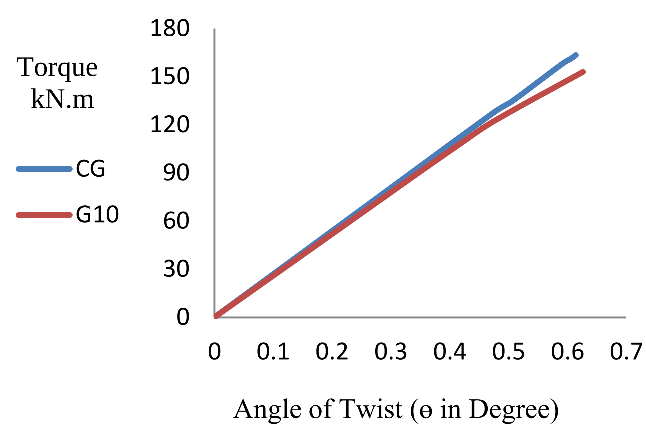


Figure 18. Torque-twist behavior for G10.

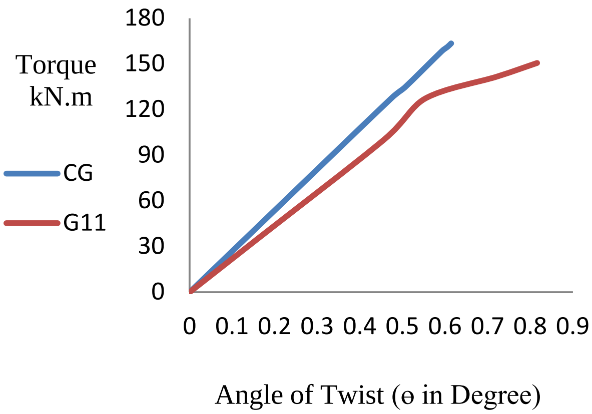


Figure 19. Torque-twist behavior for G11.

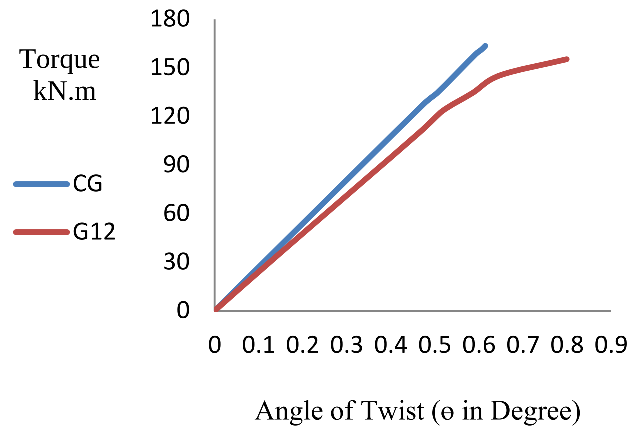


Figure 20. Torque-twist behavior for G12.

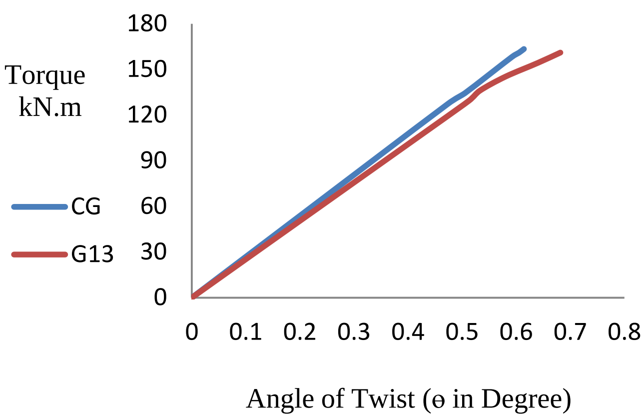


Figure 21. Torque-twist behavior for G13.

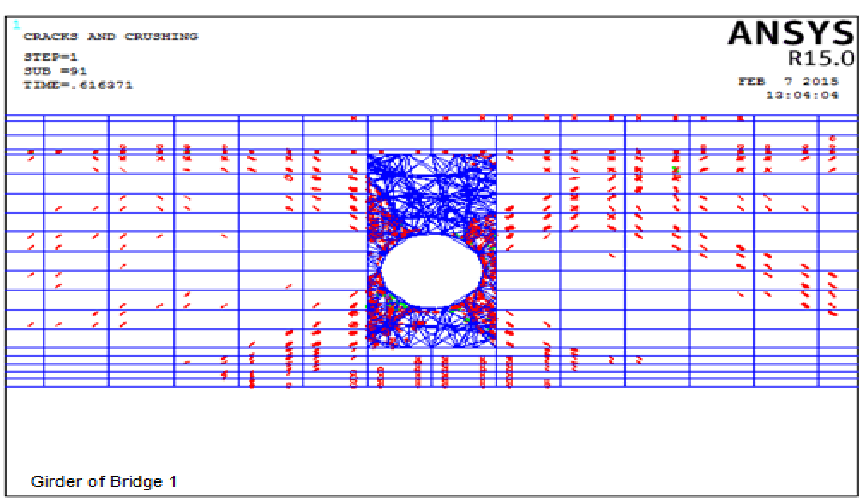


Figure 22. Numerical crack patterns around an opening.

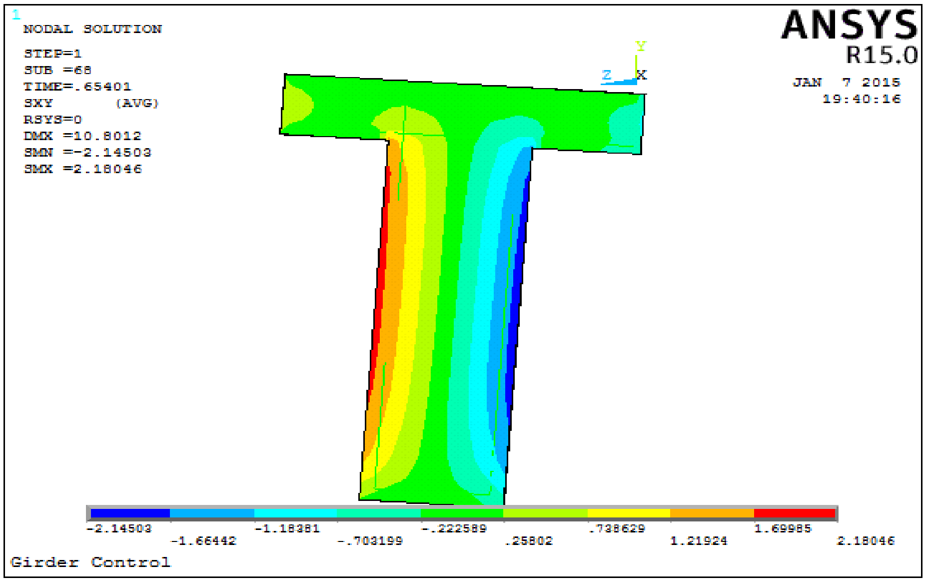


Figure 23. Numerical XY-shear stress patterns for CG.

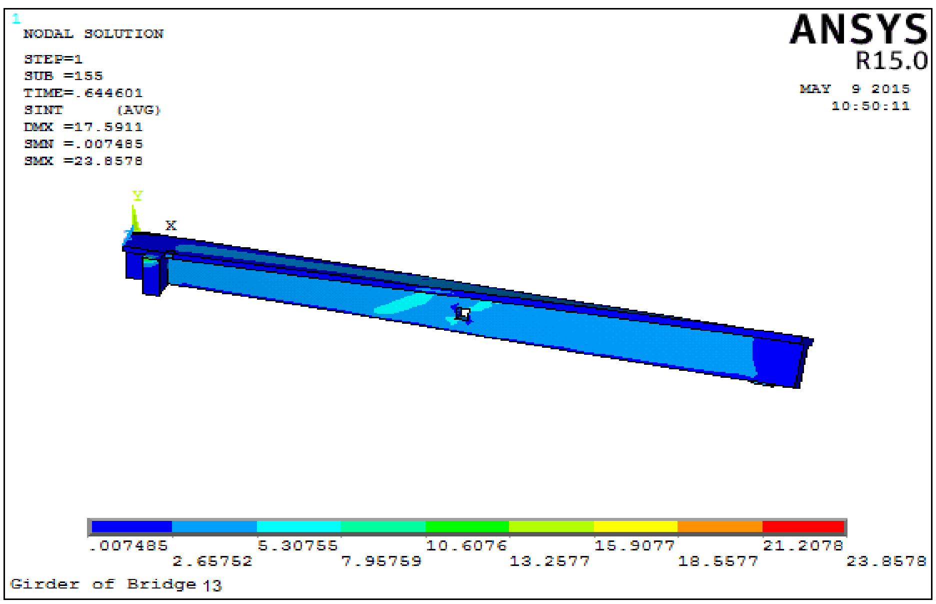


Figure 24. Numerical stress intensity of the reinforced concrete for G13**.**

Table 1. T-girders used in the modeling program.

Girder Symbol	Description
CG	Control T-girder (without web openings)
G1	T-Girder with one circular web opening at the center of the T- girder (D = 400 mm)
G2	T-Girder with one circular web openings at 1050mm from the supporting end arm of the T-girder (D = 400 mm)
G3	T-Girder with one equivalent square web opening at the center of the web (L = 360 mm)
G4	T-Girder with one circular web opening at the center of the girder (D = 600 mm).
G5	T-Girder with two circular web openings at 1050mm from the two end arms of the girder (D = 400 mm.)
G6	T-Girder with one rectangular web opening at the center of the web (L = 500 mm, H = 400 mm).
G7	T-Girder with one circular web opening with eccentricity 200 mm above the center of the web girder (D = 400 mm).
G8	T-Girder with one equivalent square web opening at the center of the web (L = 360 mm) strengthen with additional reinforcement.
G9	T-Girder with one circular web opening with eccentricity 200 mm under the center of the web girder (D = 400 mm).
G10	T-Girder with one square web opening at the center of the web (L= 400 mm).
G11	T-Girder with two circular web openings near the center of the web (L= 400 mm) and the distance between the openings is 1100 mm.
G12	T-Girder with four circular web openings near the loaded arms (L= 400 mm) and the distance between the two adjacent openings is 3100 mm.
G13	T-Girder with one equivalent square web opening at the center of the web (L = 360 mm) with increasing the additional strengthen reinforcement.

Table 2. Summary of numerical torque results.

Model Specimen	**First Cracking Torque (kN.m)**	**Ultimate Torque (kN.m)**	**%Reduction in Ultimate Torque**	**Angle of Twist at Failure (ɵ in degree)**
CG	125.6450	163.5025	-----	0.614300
G1	102.1525	156.9950	% 3.980	0.635273
G2	125.6450	158.3625	% 3.144	0.612762
G3	113.205	150.9825	% 7.657	0.614229
G4	102.1525	150.6600	% 7.854	0.623128
G5	125.6450	154.1950	% 5.693	0.630033
G6	121.3725	149.4750	% 8.579	0.620090
G7	102.1525	158.0925	% 3.310	0.677114
G8	103.9025	151.5700	% 7.298	0.609854
G9	113.2050	152.1772	% 6.927	0.613281
G10	82.9300	153.0050	% 6.420	0.626393
G11	100.230	150.6375	% 7.868	0.816267
G12	102.1525	155.2725	% 5.000	0.799121
G13	107.7950	161.1500	% 1.440	0.681792