Finite Element Analysis of Reinforced Concrete T-Beams with Multiple Web Openings under Impact Loading

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ABSTRACT

In this study, a three-dimensional finite element analysis using ANSYS 12.1 program had been employed to simulate simply supported reinforced concrete (RC) T-beams with multiple web circular openings subjected to an impact loading. Three design parameters were considered, including size, location and number of the web openings. Twelve models of simply supported RC T-beams were subjected to one point of transient (impact) loading at mid span. Beams were simulated and analysis results were obtained in terms of mid span deflection-time histories and compared with the results of the solid reference one. The maximum mid span deflection is an important index for evaluating damage levels of the RC beams subjected to impact loading. Three experimental T-beams were considered in this study for calibration of the program. All models had an identical cross-section and span similar to those of the experimental beams. The diameter of the openings of the experimental beams was 110 mm. Three other diameters were varied (50, 80 and 130) mm. The location of the face of the opening with respect to the location of impact loading was investigated (the face of the opening at distance varied 0d, 0.5d, 1d and 1.5d from the location of loading, where d is the effective depth) and the number of web openings was varied (2,4 and 6) openings. All modeled beams subjected to dropping mass of 24.5 kg with height of drop of 250 mm (as for the experimental beams). Results obtained from this study showed that the behavior of beams with circular openings of diameter equal to 22% the web depth has a small effect on the response of the RC T-beams. On the other hand, introducing circular openings with a diameter equal to 35% and 57% of the web depth (80 and 130 mm) increases the maximum mid span deflection by 23% and 43% respectively. Results also showed that, openings with a distance greater than or equal to 1.5 d from the location of impact loading have no effect on the deflection of the RC beams.

Key words: beams, web openings, impact loading.

التحليل بإستخدام العناصر المحدده لعتبات خرسانيه مسلحه ذات مقطع (T) حاويه على فتحات وتره متعدده تحت تأثير الحمل الصدمي

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الخلاصه

في هذه الدراسه تم عمل تحليل ثلاثي الأبعاد بإستخدام طريقة العناصر المحدده عن طريق البرنامج التحليلي ANSYS وذلك لتمثيل عتبات خرسانيه مسلحه ذات مقطع (T) تحتوي على فتحات وتره متعدده دائريه الشكل خاضعه لحمل صدمي. تم إعتماد ثلاث متغيرات تصميميه تضم: حجم وموقع و عدد الفتحات. تم تسليط الحمل الصدمي على 12 نموذج من العتبات الخرسانيه المسلحه بسيطة الإسناد في نقطه واحده تقع منتصف الفضاء. النتائج التي تم الحصول عليها والتي هي بدلالة مخططات هطول منتصف الفضاء مع الزمن تم مقارنتها مع نتائج النموذج المرجعي الغير حاوي على فتحات حيث إن الهطول الأقصى هو

مؤشر مهم لتحديد مستوى الضرر للعتبات الخاضعه للحمل الصدمي. تم اعتماد نتائج ثلاث عتبات مفحوصه عمليا من أجل معايرة البرنامج. جميع النماذج لها مقطع وفضاء مماثل للعتبات المفحوصه عمليا. قطر فتحات العتبات المفحوصه عمليا يساوي 110ملم. ثلاثة أقطار أخرى تم دراستها (50، 80، 130 ملم) وكذلك تم دراسة موقع الفتحات نسبة الى موقع الحمل الصدمي (بداية الفتحه تتغير بمسافة d0، d0.5، d1، d1.5 من موقع الحمل) وكذلك عدد الفتحات متغير (2، 4، 6 فتحات). النتائج المستحصله بينت أن العتبات ذات فتحات دائريه بقطر 22% من عمق الوتره لها تأثير قليل على هطولها. من ناحيه أخرى فإن عمل فتحات دائريه بقطر 35% و 57% من عمق الوتره يزيد من الهطول الأقصى لمنتصف الفضاء بنسبة 23% و 43% على التوالي. كذلك بينت النتائج بأن الفتحات ذات مسافه اكبر أو تساوي d1.5 من موقع الحمل الصدمي ليس لها تأثير على هطول العتبات الحاويه على تلك الفتحات.

1. INTRODUCTION

Web openings in beams are essential to provide a convenient passage of service ducts and pipes. As a result, story height of buildings can be reduces and slight reduction in concrete beams weight would improve the demand on the supporting frame both under gravity loading and seismic excitation which resulting in major cost saving.

Size of opening did affect strength, but an unreinforced web containing a square opening of one-quarter the web depth, or a circular opening of three-eighths the web depth, did not reduce the strength of the specimen **,ASCE-ACI Committee 426**. According to **Somes and Corley, 1974**, a circular opening may be considered as large when its diameter exceeds 0.25 times the depth of the web because introduction of such openings reduces the strength of the beam. **Mansur, et al., 1991** made an investigation on eight reinforced concrete continuous beams, each containing a large transverse opening. Their study showed that an increase in the depth of opening from 140 mm to 220 mm led to a reduction in collapse load from 240 kN to 180 kN.

In practice, there are many incidents in which the structures undergo impact or dynamic loading, such as during an explosion, transportation structures subjected to vehicle crash impact, impact of ice load on marine and offshore structures, accidental falling loads, etc. The behavior of concrete beams subjected to impact loads, is different compared to the behavior under static loading. Due to the short duration of loading, the strain rate of material is significantly higher than that under static loading conditions.

At the present time, many methods for analyzing RC members are available. One of the most powerful methods is the finite element technique which spares much time and efforts. Even though many experimental studies have been reported, limited research studies have been done on reinforced concrete T-beam with multiple web openings under impact loading by simulation. In order to verify the finite element model, three experimental beams (a solid beam without openings and two other beams with four and six un-strengthened circular openings provided in the study of **Oukaili,** and **Shammari, 2013** were considered in this study.

2. OBJECTIVES AND SCOPES

The purpose of this study is to investigate the effect of size, location and number of circular web openings on the impact response of RC T-beams without strengthening of the openings by additional reinforcement. This research study focuses on three variables:

1. Diameter of openings (50, 80, 110 and 130 mm).
2. Location of openings with respect to the location of impact loading (clear distance between the impact load and the beginning of opening = 0d, 0.5d, d and 1.5d)
3. Number of web openings (2, 4 and 6 openings).

The scope of this study is to simulate simply supported RC T-beams with the mentioned variables under transient (impact) loading using **ANSYS 12.1** program to obtain mid span deflection-time histories and compare them with the solid reference beam.

All T-beams have identical dimensions and reinforcement based on Oukaili and Shammari (2013) experimental beams. Thickness of flange =60mm, width of flange =300mm, depth of web =230mm and width of web =120mm. Beam length =2000mm with an effective span of 1800mm. All beams were reinforced with 2 ∅ 20mm longitudinal bars as tension reinforcement, four ∅ 6 mm longitudinal bars as compression reinforcement and ∅ 4 mm at 130 mm center to center as stirrups. The dimensions and details of reinforcement are shown in **Fig. 1a.**

Fig. 1b-1d shows the details of the experimental beams which were considered in this study for calibration of the program. The distance between the end of the first opening (near the support) and the support equals 130 mm; this is about half the effective depth. The centers of the circular openings were located at 145 mm along the y-direction from soffit of the beam. Diameter of openings is 110mm (0.48 the web depth).

3. MODELS SPECIFICATIONS

3.1 Material Properties

3.1.1 Concrete

Concrete is a quasi-brittle material and has different behavior in compression and in tension. Solid65 element was used to model this material. This element has eight nodes with three degrees of freedom at each node - translation in the nodal x, y, and z directions. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. A schematic of the element is shown in **Fig. 2 ANSYS Manual, Version 12.1**. Smeared cracking approach has been used in modeling the concrete in the present study **William,** and **Wranke, 1975**. Poisson's ratio (ν) for concrete was assumed to be 0.2 ,**Bangash, 1989**. Self-weight of the beams was considered.

3.1.2 Reinforcement

Modeling of reinforcing steel in finite elements is much simpler than the modeling of concrete. A Link 8 element was used to model steel reinforcement. This element is a three dimensional spar element and it has two nodes with three degrees of freedom -translations in the nodal x, y, and z directions. This element is also capable of plastic deformation. This element is shown in **Fig. 3**. A perfect bond between the concrete and steel reinforcement is considered. However, in the present study the steel reinforcing was connected between nodes of each adjacent concrete solid element, so the two materials shared the same nodes. The steel for the finite element models is assumed to be an elastic-perfectly plastic material and identical in tension and compression. A Poisson's ratio of 0.3 is used for the steel reinforcement.

3.2 Boundary Conditions and Loading

Taking advantages of the symmetry, only quarter of the beam was modeled. Rollers were used to show the symmetry condition at internal faces, whereas the nodes at the support were restrained against vertical displacement.

Transient dynamic analysis (sometimes called time-history analysis) is a technique used to determine the dynamic response of a structure under the action of any general time-dependent loads. This type of analysis can be used to determine the time-varying displacements, strains, stresses, and forces. Three methods are available in ANSYS program to do a transient dynamic analysis: full, mode superposition, and reduced. ANSYS analysis was done using the reduced method; this method condenses the problem size by using master degrees of freedom and reduced matrices. After the displacements at the master DOF have been calculated, ANSYS expands the solution to the original full DOF set. Multiple load steps are usually required to specify the load history in a transient analysis. The first load step is used to establish initial

conditions, and second and subsequent load steps are used for the transient loading. **Fig. 4** shows FE mesh, boundary conditions and load step.
Damping has much less importance in controlling the maximum response of a structure to impact loads than for periodic or harmonic loads because the maximum response to a particular impulsive load will be reached in a very short time, before the damping forces can absorb much energy from the structure, **Clough, 2003**, for this reason only the undamped response to impact loads will be considered in this study.

4. VERIFICATION STUDY

The finite element analysis calibration study includes modeling of RC T-beams with dimensions and properties corresponding to solid beam and two other beams with four and six circular web openings of diameter equals 110mm tested by **Oukaili**, and **Shammari, 2013**. 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 test setup of the experimental beams is shown in **Fig.5**.
Transient analyses were made for dropping mass of 24.5 kg and height of drop of 250 mm for the three experimental beams. Finite element analysis results in terms of mid span deflection-time histories are shown in **Fig. 6**. In general, the agreement is good and the plots have similar trends.

5. PARAMETRIC STUDY

Results and discussion can be presented in three sections according to the parametric study. In the first section, the finite element modeling of the reinforced concrete beams with circular openings in varying diameters (50, 80, 110 and 130 mm) will be discussed. In the second section, the discussion will be made about the effective location of the opening with respect to the location of the impact loading. In the third section, the effect of different number of openings (2, 4 and 6) will be presented. These modeled beams have the same dimensions as the experimental beams tested by **Oukaili**, and **Shammari, 2013**. Twelve models were needed for this study; details of these models were presented in **Table 1**.

6. RESULTS AND DISCUSSION

6.1 Effect of Size of Web Openings

The transient (impact) response of four RC modeled beams with six openings of distance between the point of applied load and the beginning of first opening equals 0.5d and with variable diameter, 50, 80, 110 and 130 mm, was studied. From the analysis results, it was found that the maximum mid span deflection of the modeled beam with six openings, each of 50 mm diameter was 2.44 mm while that for the solid one was 2.24 mm. The increase in the maximum mid span deflection was 8%. Hence, introducing openings with a diameter equal to 22% the web depth of the beam has a small effect on the deflection of the beam.
On the other hand, it was found that the maximum mid span deflections of the modeled beams of six openings with 80, 110 and 130 mm diameter six openings were 2.74, 3 and 3.2 mm. The increase in the maximum mid span deflection was 23%, 34% and 43% compared to the solid beam. **Fig. 7** shows the effect of the size of openings.

6.2 Effect of Location of Web Openings

In this section, the effective location of the opening with respect to the location of the impact loading that affect the response of the RC beam can be found. Four different locations of two symmetrical openings were studied, 0d, 0.5d, d and 1.5d from the point of impact loading to the beginning of the opening. It was found that as the distance of the opening from the point of impact loading increases, the effect of opening on the response of the RC beams in terms of mid span deflection-time history decreases till this distance reach 1.5 d ;at this distance, the opening has no effect on the mid span deflection-time history of the beam. **Fig. 8** shows the effect of the location of openings.

6.3 Effect of Number of Web Openings

In this section, the effect of number of web openings with different locations along the span of the modeled beams on the impact response of RC beams was presented. From the analysis results it can be found that the maximum mid span deflections for the modeled beams are of approximately equal values when the distance of the opening is 0.5d from the applied load location, regardless the number of web openings (2, 4 or 6 openings). Modeled beam with six openings which were distributed one close to the other in the middle part of the beam web showed maximum mid span deflection of 56% greater than that of the solid beam. **Fig. 9** shows the effect of number of openings of different locations on the mid span deflection-time history.

7. CONCLUSIONS

The following conclusions can be obtained from the analysis results. The conclusions are based on transient analyses which made by dropping mass of 24.5 kg and height of drop of 250 mm as in the experimental beams:

1. Introducing openings with a diameter equal to 22% the web depth of the beam causes an increase in the maximum mid span deflection by 8%.
2. The increase in the maximum mid span deflection is 23%, 34% and 43% for beams with six openings with 80, 110 and 130 mm diameter respectively, compared to the solid beam.
3. As the distance of the opening from the point of impact loading increases, the effect of opening on the response of the RC beams in terms of mid span deflection-time history decreases till this distance reaches 1.5 d; at this distance, the opening has no effect on the mid span deflection-time history of the beam
4. The maximum mid span deflections for the modeled beams are of approximately equal values when the distance of the opening is 0.5d from the applied load location, regardless the number of web openings.
5. Modeled beam with six openings which were distributed one close to the other in the middle part of the beam web showed maximum mid span deflection of 56% greater than that of the solid beam.

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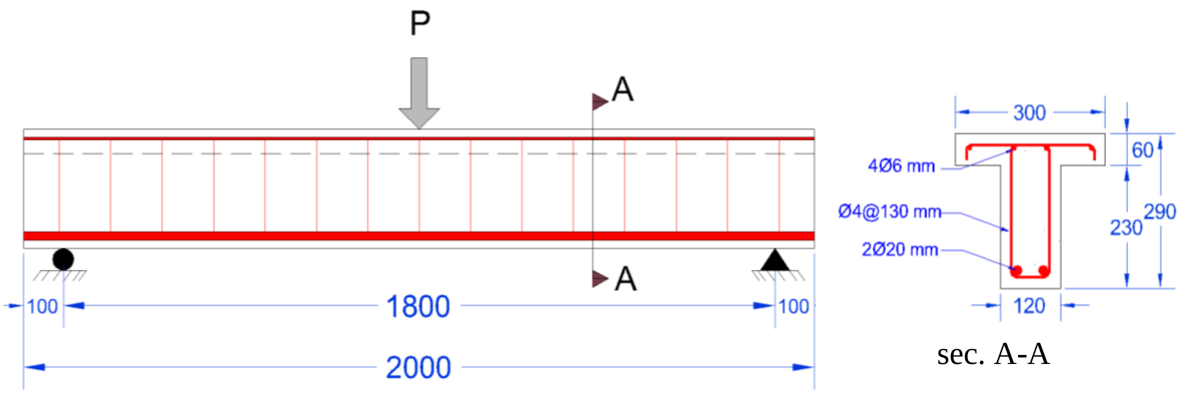
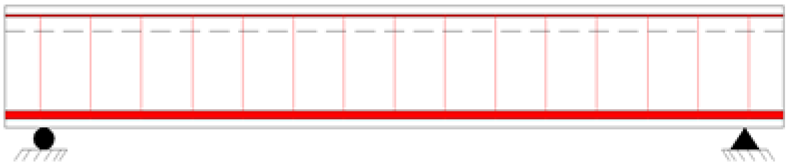
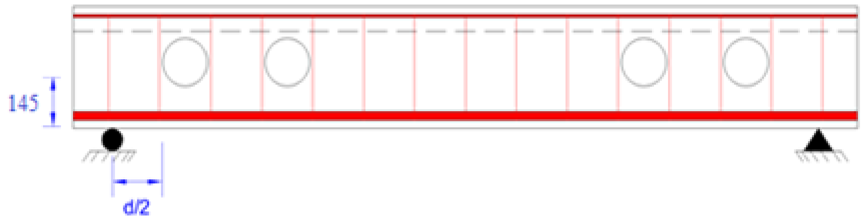


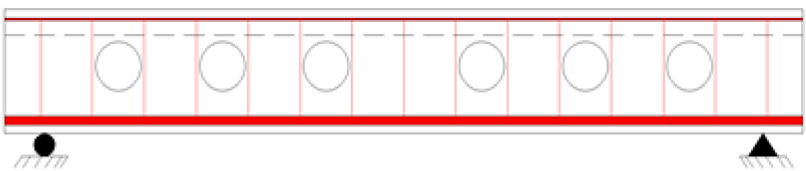
a. Dimensions and reinforcement details of experimental beams.



b. Solid beam (first experimental beam).



c. Beam with four circular openings (second experimental beam).



d. Beam with six circular openings (third experimental beam).

Figure 1. Details of the experimental b.

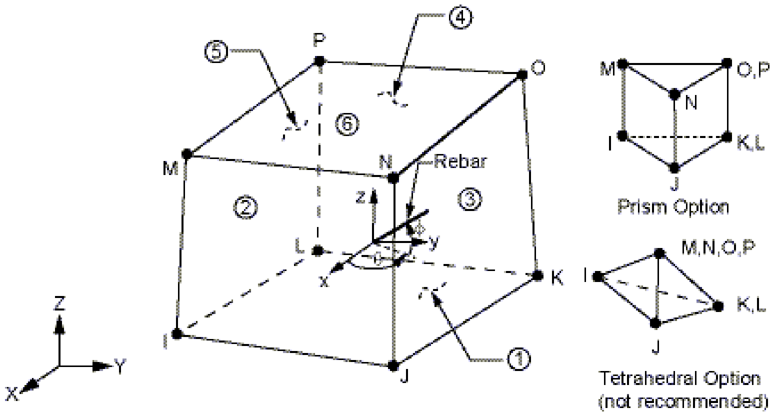


Figure 2. Solid 65 element geometry.

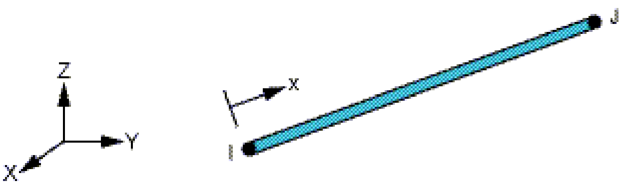


Figure 3. Link 8 element geometry.

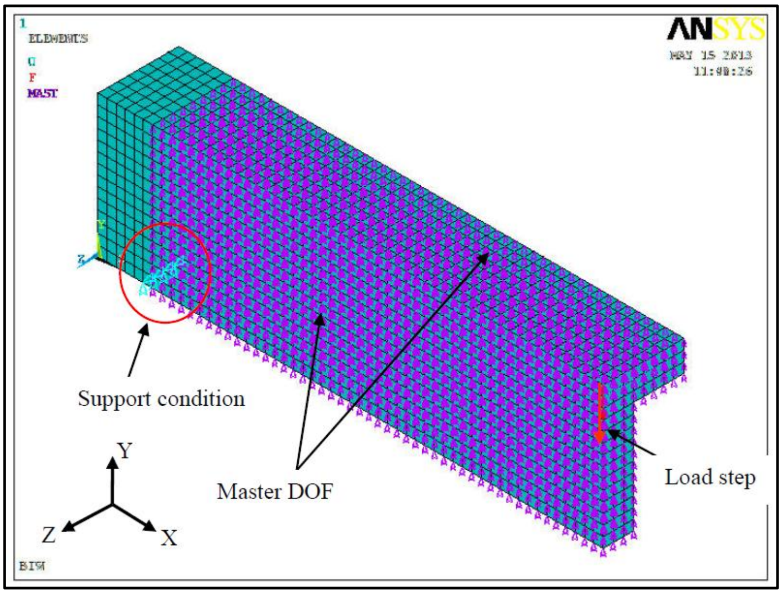


Figure 4. FE mesh, boundary conditions and load step.

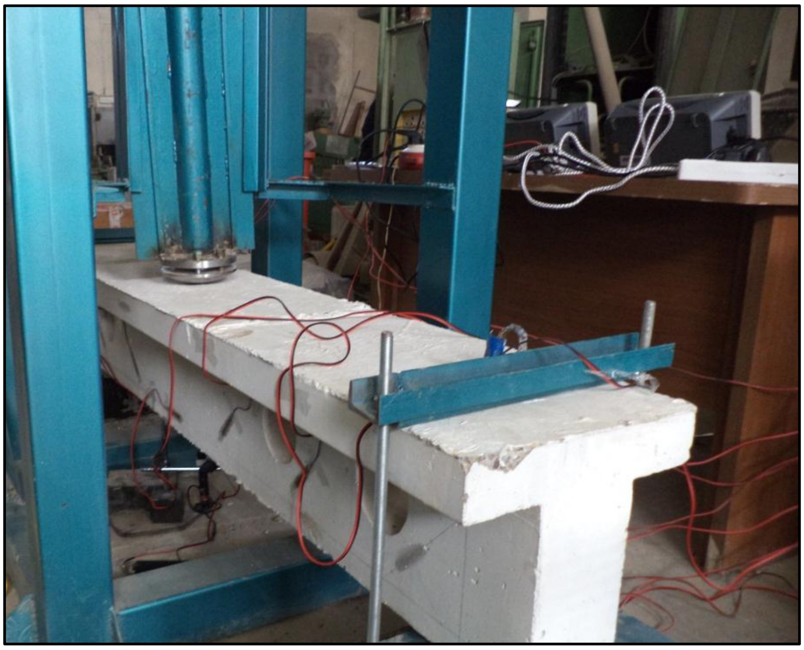


Figure 5. Test setup of experimental beams.

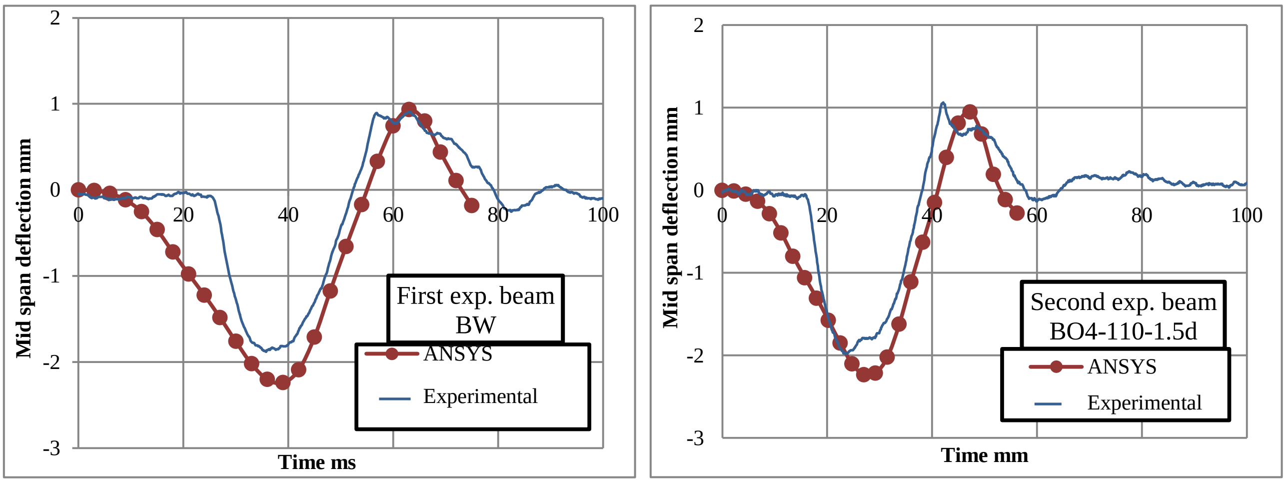


Figure 6. Comparison of predicted results to test results for mid span deflection-time histories for the calibration beams.

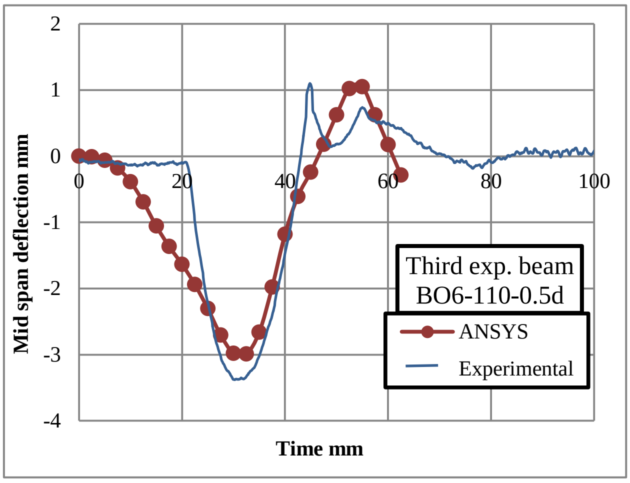


Figure 6. Continue, Comparison of predicted results to test results for mid span deflection-time histories for the calibration beams.

Table 1. Details of the modeled beams.

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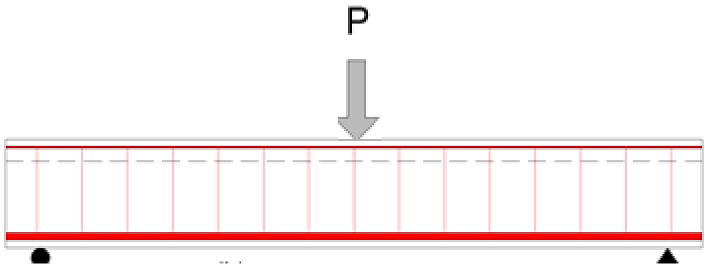
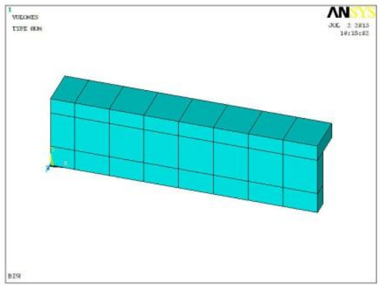
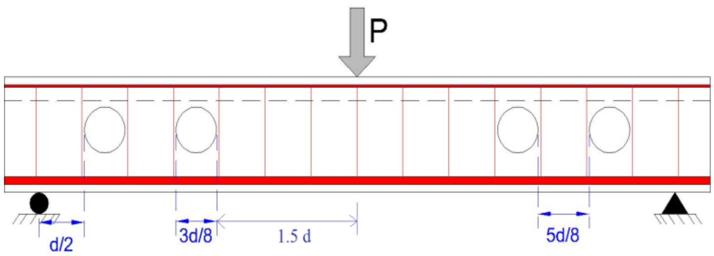
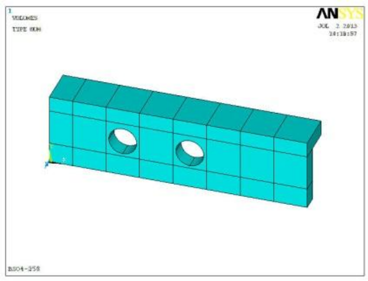
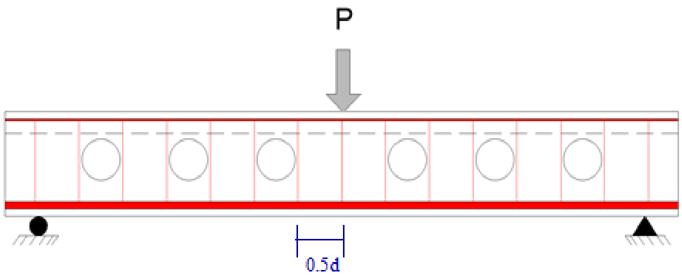
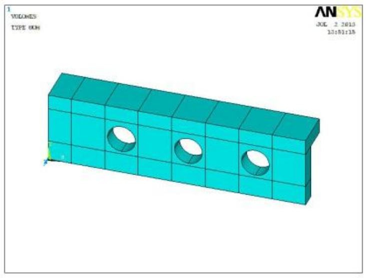
<tr><td>*BW</td><td>
</td><td></td></tr>
<tr><td>*BO4-110-1.5d</td><td>
</td><td></td></tr>
<tr><td>*BO6-110-0.5d</td><td>
</td><td></td></tr>
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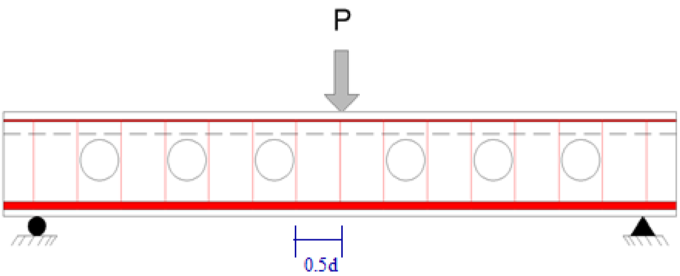
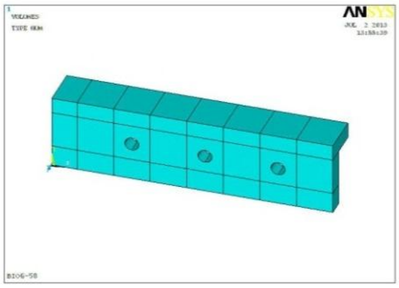
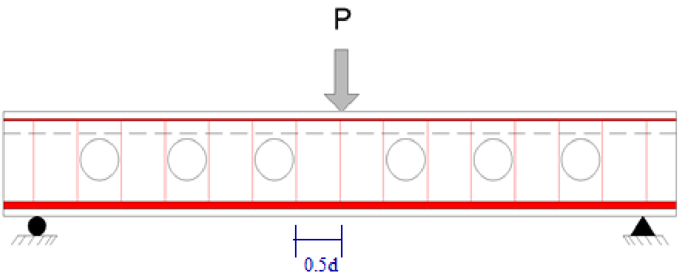
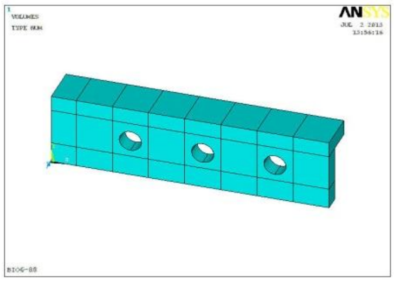
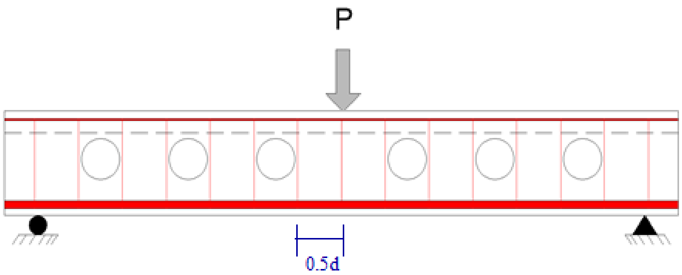
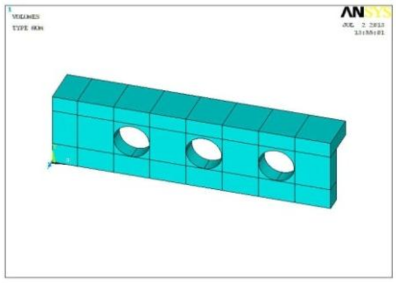
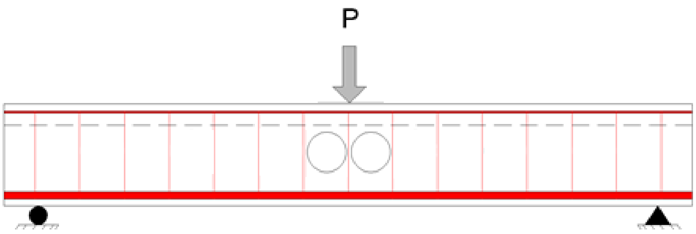
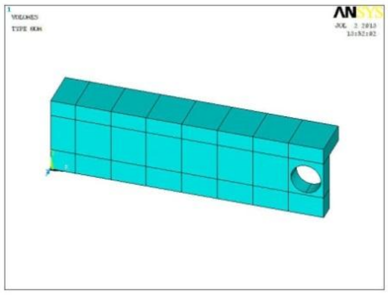
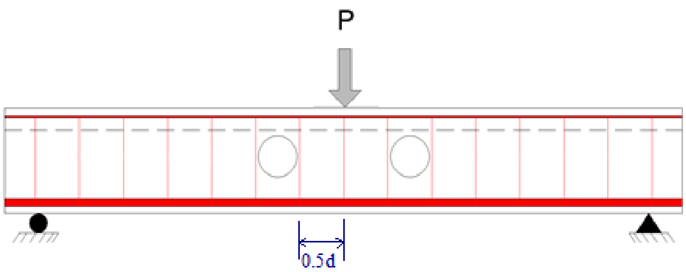
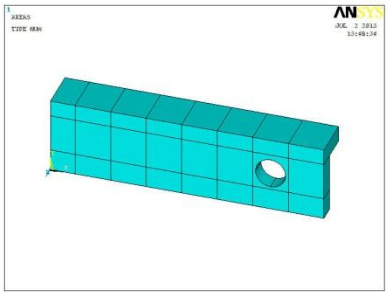
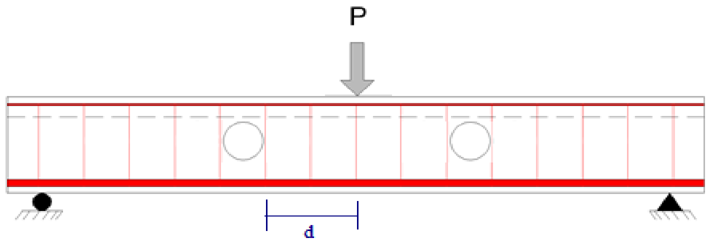
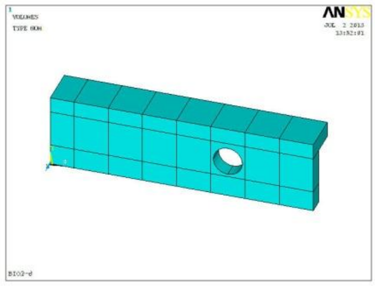
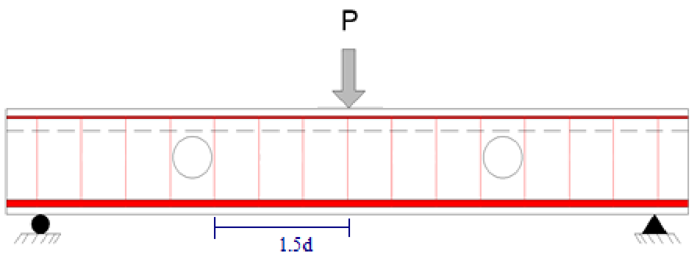
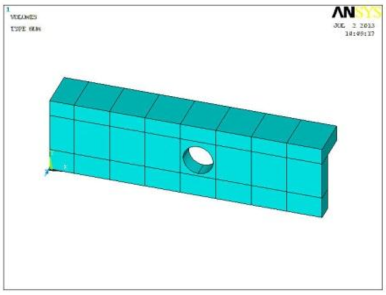
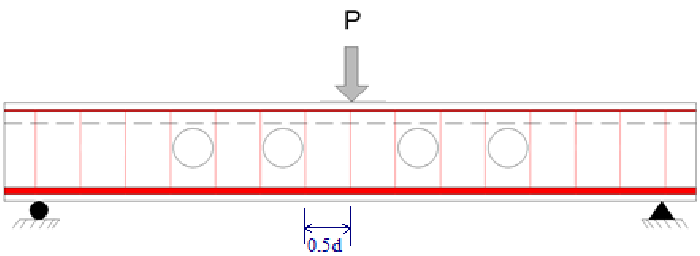
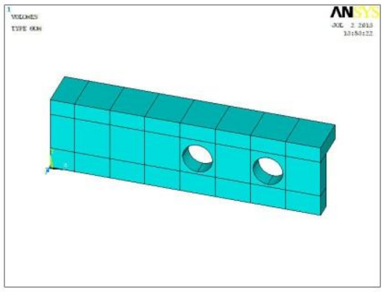
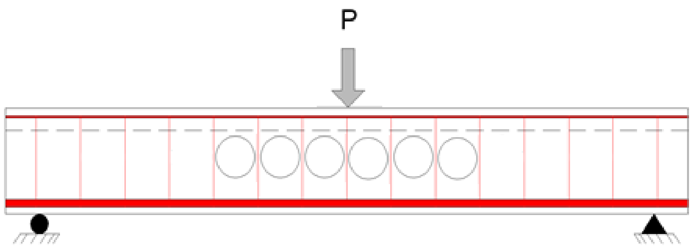
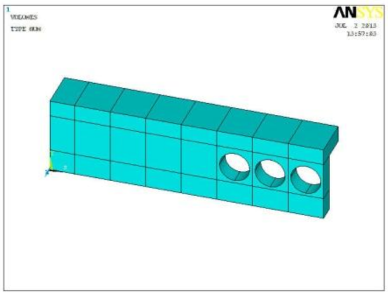
**BO6-50-0.5d		
BO6-80-0.5d		
BO6-130-0.5d		
BO2-110-0d		
BO2-110-0.5d		

BO2-110-d		
BO2-110-1.5d		
BO4-110-0.5d		
BO6-110-Mid		

*Experimental beams.

Designation **BO6-50-0.5d (for example): **B**eam with **6** **O**penings, opening diameter = **50** mm and the distance between the point of applied load and the beginning of first opening is **0.5d**.

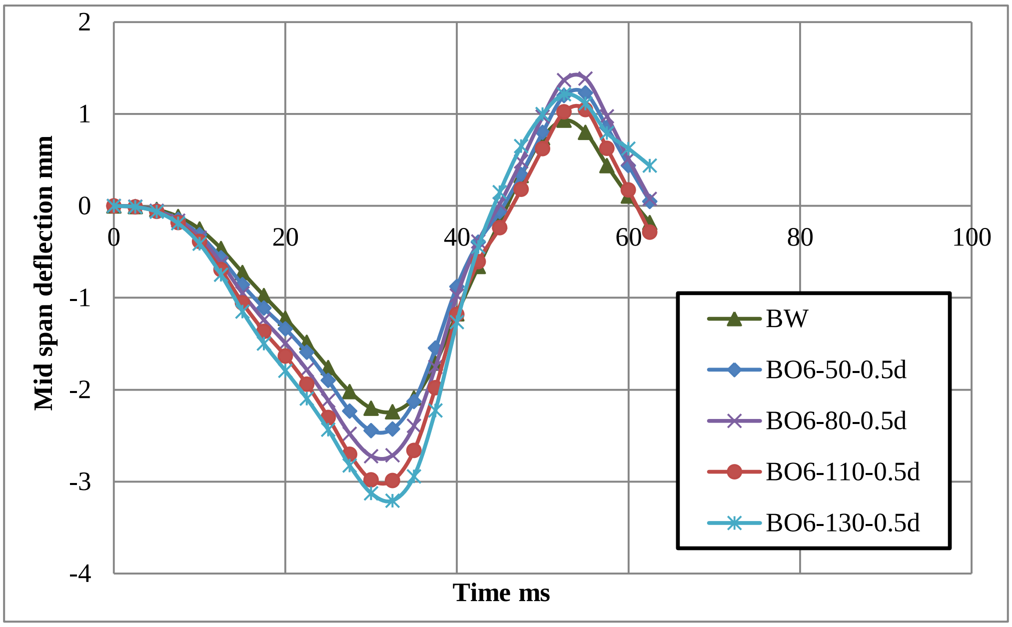


Figure 7. Effect of size of circular web openings on mid span deflection-time histories from ANSYS analyses.

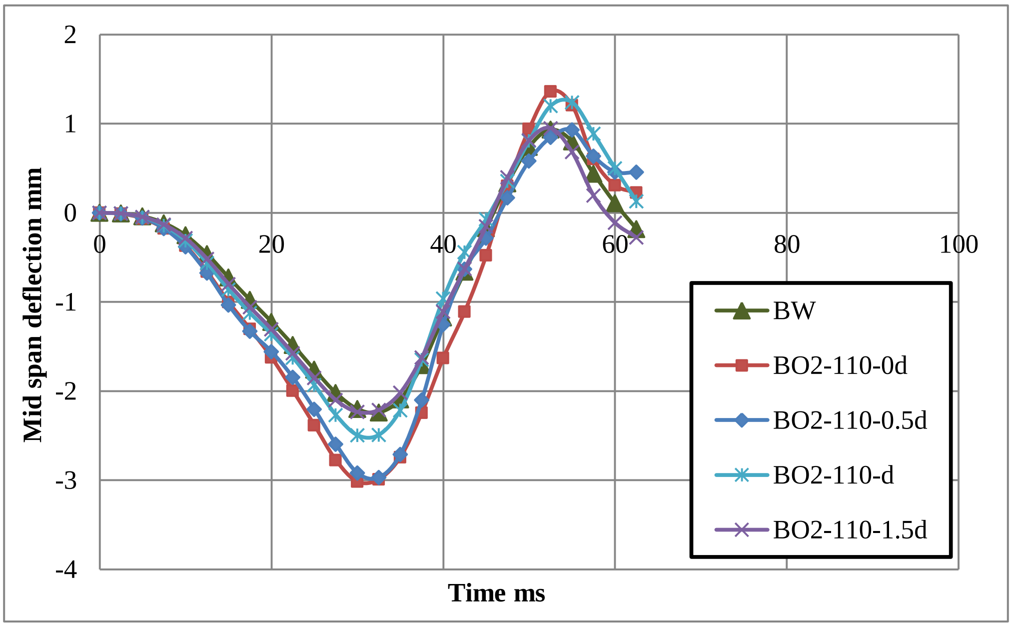
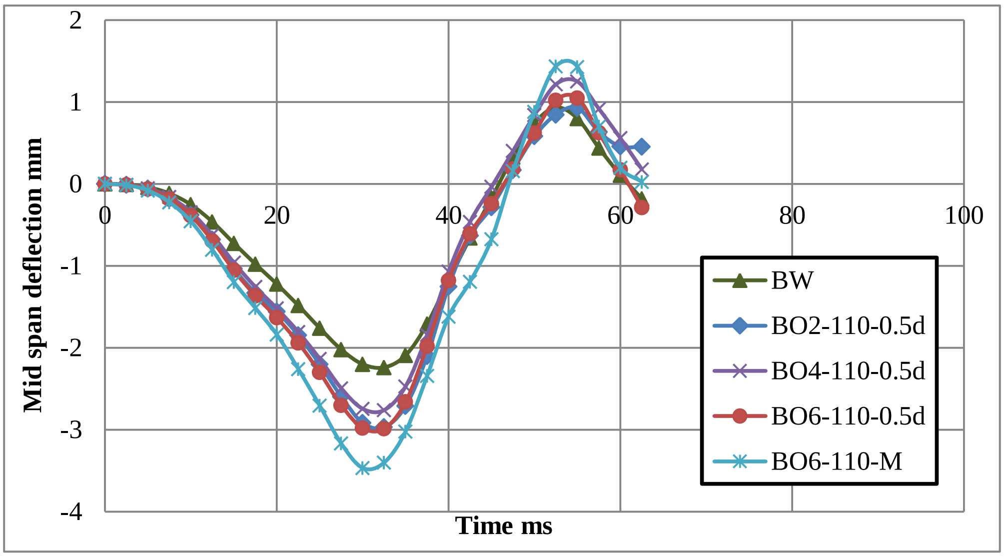


Figure 8. Effect of location of web openings on mid span deflection-time histories from ANSYS analyses.



Figue 9. Effect of number of web openings on mid span deflection-time histories from ANSYS analyses.