Structural Behavior of Composite Castellated Steel Concrete Beams Subjected to Impact Load

Shereen Q. Abdulridha

Babylon Technical Institute, Al-Furat Al-Awsat Technical University, 51015 Babylon, Iraq
Department of Civil Engineering, University of Technology, Baghdad, Iraq.

shereen_qasim@yahoo.com

Haitham H. Muteb
Department of Civil Engineering, University of Babylon, Hillah 51002, Iraq.

dr_haitham_67@yahoo.com

Sarmad Sh. Abdulqader

Department of Civil Engineering, University of Technology, Baghdad, Iraq.

saas7703@yahoo.co.uk

Submission date:- 16/9/2018	Acceptance date:24/9/2018	Publication date:-1/10/2018

Abstract

The structural behavior of composite castellated steel concrete beams subjected to impact load presented in this study. In which fabrication of composite castellated steel self-compacting concrete beams which connected to self-compacting concrete by means of stud shear connectors. Four composite castellated beams were performed with different degrees of castellation, they were 0%, 25%, 33.8% and 50%. These specimens were subjected to an impact load produced from free falling of steel ball. The experiments required fabrication of special rig which connected with different sensors and programmed by Lab VIEW 2016 program. Different parameters were recorded and discussed which involved force-time history and displacement history for the tested beams. It is founded that the increase of the degrees of castellation for the adopted specimens will increase the maximum impact load by about 16.13%, compared with non-castellated composite specimen. The amplitudes of vibration represented by displacement have decreased with the increasing of degrees of castellation by about 3.51%, 14.04% and 20.18% for the degrees of castellation 25%, 33.8%, and 50% respectively.

Key words: Castellated beam, Composite steel concrete beam, Displacement response, Force response, Impact load, Self-compacting concrete.

1. Introduction

The structural engineers do their best in order to gain high strength to weight ratio by using castellated beams. Castellated beam is structural member which is fabricated from cutting I-section steel beam in a special manner then welding, producing opening through the web [1]. The depth of the new section is enhanced by a specific percentage, so as to increase the performance of the beam against bending. This percentage is known as degree of castellation, where it represents the percentage of increasing the depth of the new section to the original section. Impact load is one of the dynamic loads that expected to occur during manufacture, service or maintenance period of the structure, for example dropping a heavy tools. Thus the researchers and designers paid attention to the effect of dynamic loads as well as the static loads. There are number of studies specialized in reinforced concrete members, under the effect of drop weight of impact tests in addition to the steel members, whereas most of the previous studies interested of composite beams were analytically and limited studies utilize laboratory tests. Different kinds of reinforced concrete slabs were subjected to loads with various rates by [2].

They tested the specimens experimentally and numerically. According to the observations, the loading rate has substantial relationship with mode of failure. Also, they cited that the deformation and modes of failure might change when the rate of subjected concentrated load changes from static load, low and high rates. Five composite castellated beam has different lengths and also various shear to moment ratios were tested numerically and experimentally by [3], in order to study the flexural and shear behavior. It was noticed that the longer flexural castellated beams have lateral torsional buckling of the compression flange, while the other beams failed when lateral torsional buckling existed in the web post. An experimental test for different shapes of openings used in cantilever castellated beams was provided by [4], which were: square, hexagonal and circular. Three sets of the castellated beam were analyzed to explain the effect of openings forms on the behavior of web post-buckling. They used the package software ANSYS 14.0 for checking the buckling behavior of the webs, which represents that the resulting increased of stress towards the edge of web openings, develops a premature buckling over the web openings. Two composite beams were performed so as to study the impact behavior produced by falling mass on these beams by [5]. Two types of concrete with different strength were included. It was found that the maximum impact force of specimen with self-compacting concrete is little more than the maximum impact force for the corresponding specimen with normal concrete by percentages not exceed19.35%.

2. Experimental Program

Four castellated beams were connected to a slab of self-compacting concrete by stud connectors to produce the composite beams. Different degrees of castellation were adopted, they were 0%, 25%, 33.8% and 50% to study their effects on the beams when subjected to impact load. The impact load was produced from free falling of a steel ball with kinetic energy about 102 Joule. The steel ball weighs 7 kg and falls from 1.5 m height, was used to strike these specimens three times.

2.1. Fabrication Processes

The rolled I-section steel girders were cut into two parts using a special machine (CNC) in a zigzag manner, then one part is little shifted, then they are welded accurately to produce hexagonal openings, so increasing the depth of the new section with specific degree of castellation. Figure 1 shows clarification to the pertinent dimensions established in the present study. The dimensions were established in accordance with the following equations:

$$D = d * (\lambda + 1) * 100 \tag{1}$$

$$a = \frac{(D - d)}{sin60} \tag{2}$$

$$h_p = \frac{d - a.sin60}{2} \tag{3}$$

Where

a = Throat width (the length of one side of the hexagonal opening)

h_p = Throat depth (the height of the point of starting cut of the web)

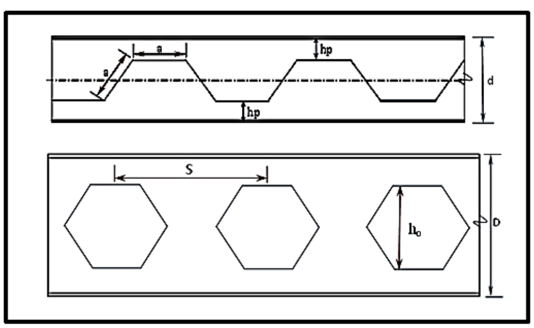

Figure 1. Relevant Characters of Castellated Beams

2.2. Dimensions and Details of Beams

The total specimen length is 1628 mm, and width of concrete slab is 350 mm and its thickness is 70 mm. The dimensions of rolled steel I-section are: d=137.5 mm, t_f=4.1 mm, b_f=71 mm, and t_w=5.1 mm, while the depth of the castellated section is variable, depends on the adopted degree of castellation. Minimum steel reinforcement was provided as one layer in the concrete slab with deformed bars with diameter 6 mm. Studs shear connectors with length 55 mm and diameter 10 mm are used in one row and spacing 79.3 mm. Pairs of stiffeners had welded at the thirds locations and at the supports of the beams. Table 1 explain the detail of specimens dimensions. Figures 2 to 5 present the plan and dimensions of the composite beams fabricated to be tested under impact load.

Table 1. Detail of Beams Dimensions.

Description	Dimensions of Parameters						
	λ^a(%)	d(mm)	a(mm)	h_o(mm)	h_p(mm)	S(mm)	D(mm)
Solid composite beam	0	137.5	----	----	----	----	----
Composite castellated beam	25	137.5	39.67	68.7	51.52	119	171.75
Composite castellated beam	33.8	137.5	52.89	91.61	45.59	158.67	183.83
Composite castellated beam	50	137.5	79.33	137.41	34.33	238	206.1

[a] λ: Degree of castellation

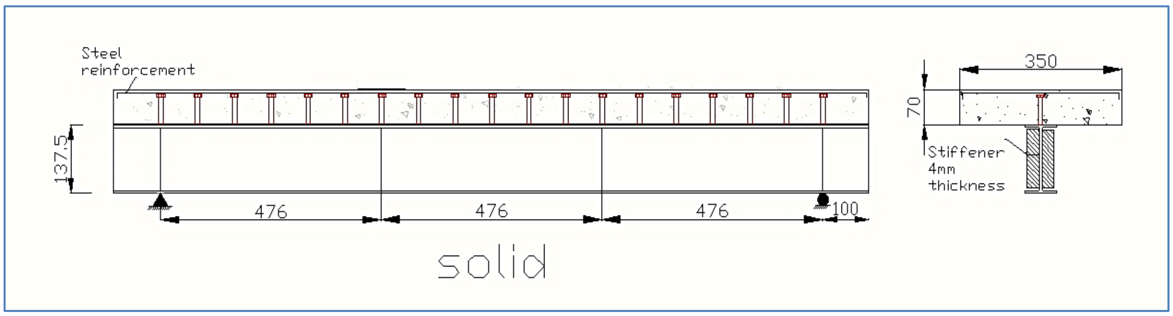

Figure 2. Solid (parent) Composite Beam (λ= 0%)

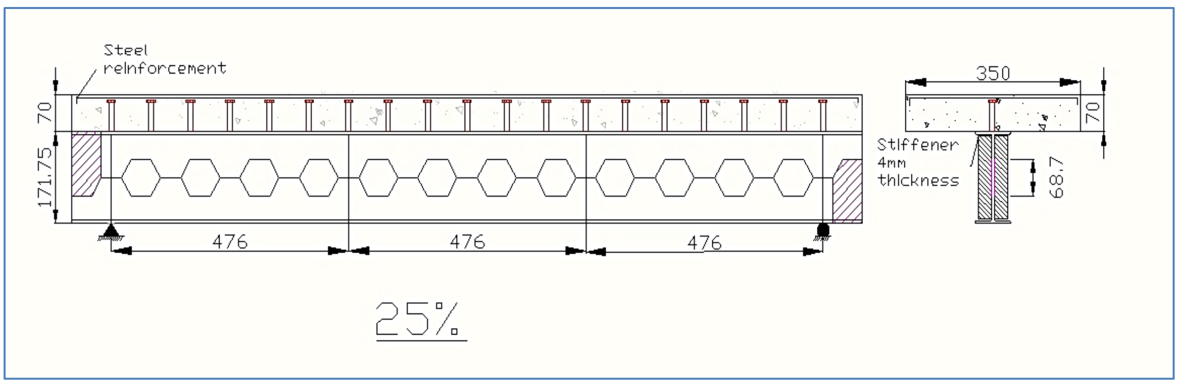

Figure 3. Plan of Composite Castellated Beam (λ=25%)

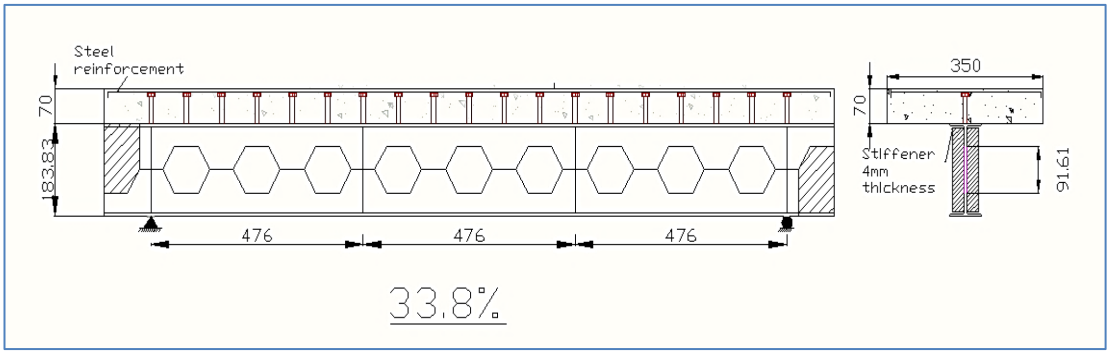

Figure 4. Plan of Composite Castellated Beam (*λ*=33.8%)

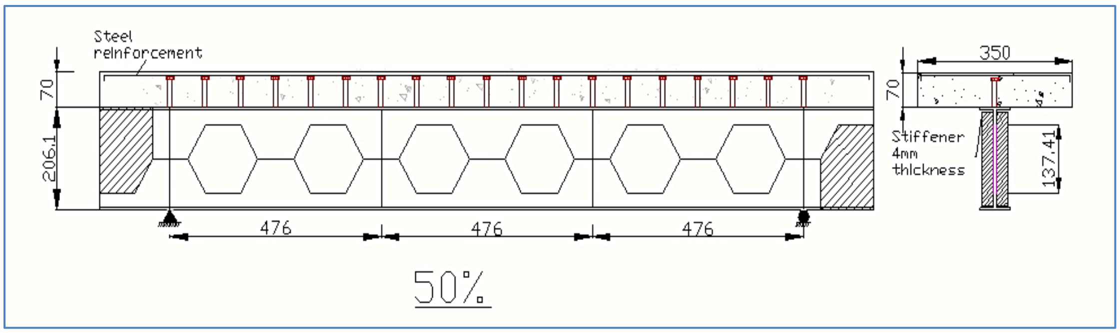

Figure 5. Plan of Composite Castellated Beam (*λ*=50%)

2.3. Properties of Concrete and Steel Components

The concrete materials used to produce self-compacting concrete complied to the Iraqi 1985 specifications and ASTM specifications [6]. The concrete mix is designed according to the guidelines of (EFNARC) [7] for achieving compressive strength about 50 MPa. Properties of steel components including rolled I-section, studs connectors, stiffeners and steel reinforcement are introduced in Table 2, in addition to the mechanical specifications of concrete.

Table 2. Properties of Steel Components and Concrete.

Material	Description	Unit	Value
I-beam section	Yield strength	MPa	322.33
	Ultimate tensile strength	MPa	466.67
	Modulus of elasticity	MPa	201003
	Elongation	%	9.42
Studs connectors	Head diameter	mm	17
	Shank diameter	mm	10
	Length	mm	55
	Yield strength	MPa	447.67
	Ultimate tensile strength	MPa	696.67
Reinforcement bar	Yield strength	MPa	670
	Ultimate tensile strength	MPa	738
	Equivalent steel bar diameter	mm	5.96
Self-compacting concrete	f_{cu}	MPa	61.1
	f'_c	MPa	51.8
	f_r	MPa	8.04
	f_{sp}	MPa	3.79
	E	MPa	34000

2.4. Test Rig and Sensors

A steel rig was manufactured especially to produce impact load on beams specimens and recording tests results. Sensors adopted in the tests include load cells, laser sensor, photo cells, LVDT, magnetic sensors, crackmeter and data acquisition. The sensors need to calibrate were calibrated before the tests in the Laboratory of Mechanical Engineering of The University of Technology. A program is designed particularly for operating the sensors and saving results of the present tests using Lab VIEW 2016. The tests of the composite castellated beams were carried out in a field laboratory intended for the present experimental work. Pair of magnetic sensors and pair of photocells sensors were fastened in the rig to compute the velocity of falling of the steel ball. It was 5.0 m/s, this value has been checked with the velocity calculated from the kinematic motion of falling mass (Equation. 4 from which, $V = 5.43\ m/s$), thus the result can be considered acceptable.

$$V = \sqrt{2gh} \tag{4}$$

It is well known any electrical device should be connected to a grounding system, so three copper rods had planted in 1.2 m holes depth, and each one was connected by steel wire for grounding the parts of the rig and the computer. Plate 1 shows preparing the grounding system, whereas Plate 2 shows the test rig and sensors used in the present study.

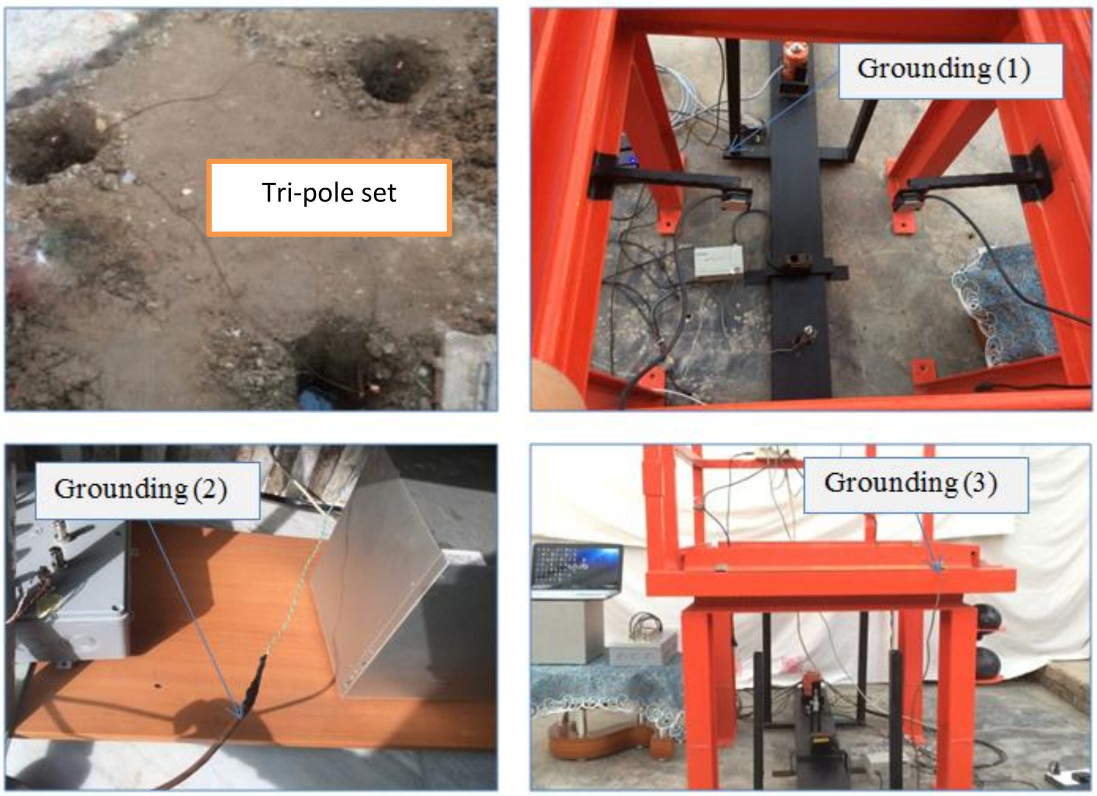

Plate 1. Grounding System

3. Results

3.1. Displacement History

The deflection response at midspan of the tested beams were recorded for three sequent strikes. It can be noticed that the response of deflection for the second and third strike have some lag in the transformation velocity of the wave and some increase in the amplitude if compared with the response for the first strike and they take more time to settle down. That may be attributed to rather decreasing of the beam stiffness caused by the previous strike or strikes. So the velocity of wave transformation decreased.

Figures 6 to 9 represent the displacement history of composite beams specimens. The sequent strikes caused increasing the maximum amplitude occurred had been recorded of the displacement history, that's attributed to rather decreasing of the stiffness of the specimen after each strike. The percentages of amplitude increasing after the third strike compared with the effect of first strike were about 23%. It can be noticed that as the degree of castellation increases the time required to settle down decreased, i.e. the fluctuation of displacement is damped quickly. Also, the amplitudes of vibration decreased as the degree of castellation increased, where the percentage of decrease depending on the solid specimen were 3.51%, 14.04% and 20.18% for the degrees of castellation 25%, 33.8%, and 50% respectively.

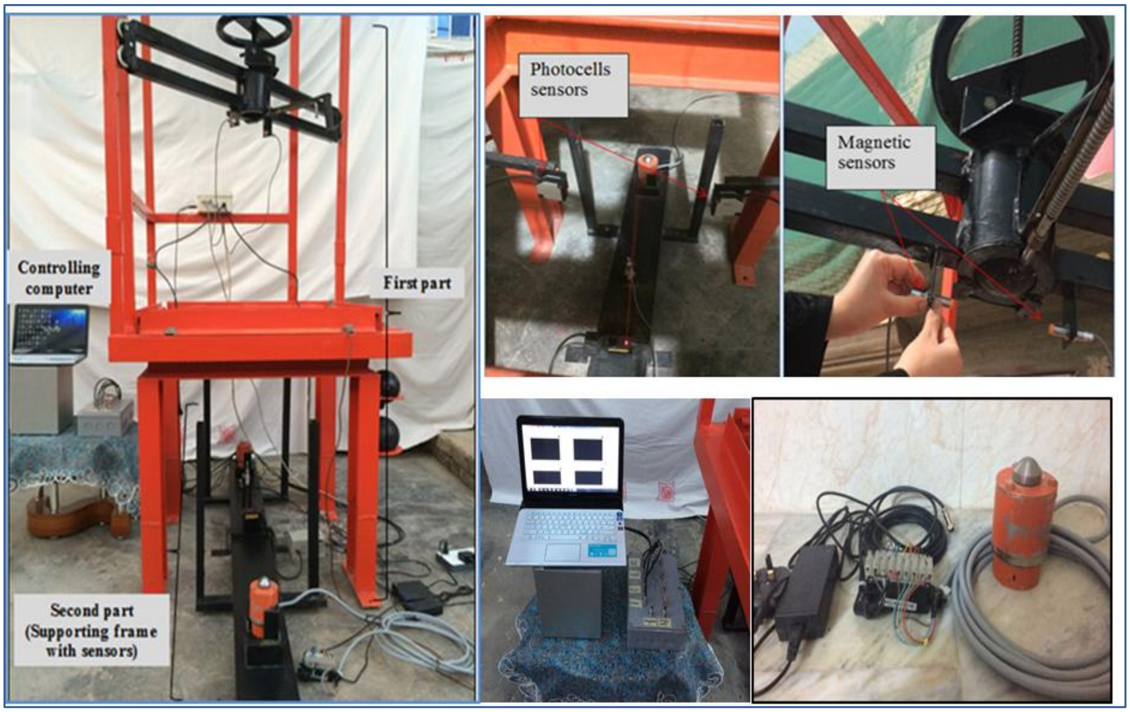

Plate 2. Test Rig with all Sensors and Data Acquisition

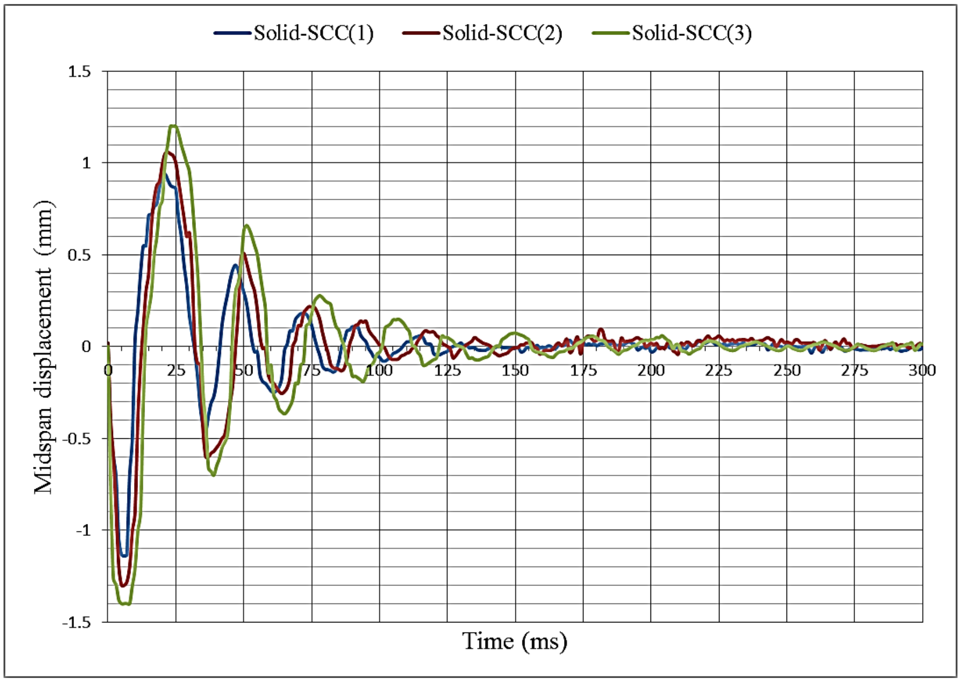

Figure 6. Displacement–History of Solid Composite Beam

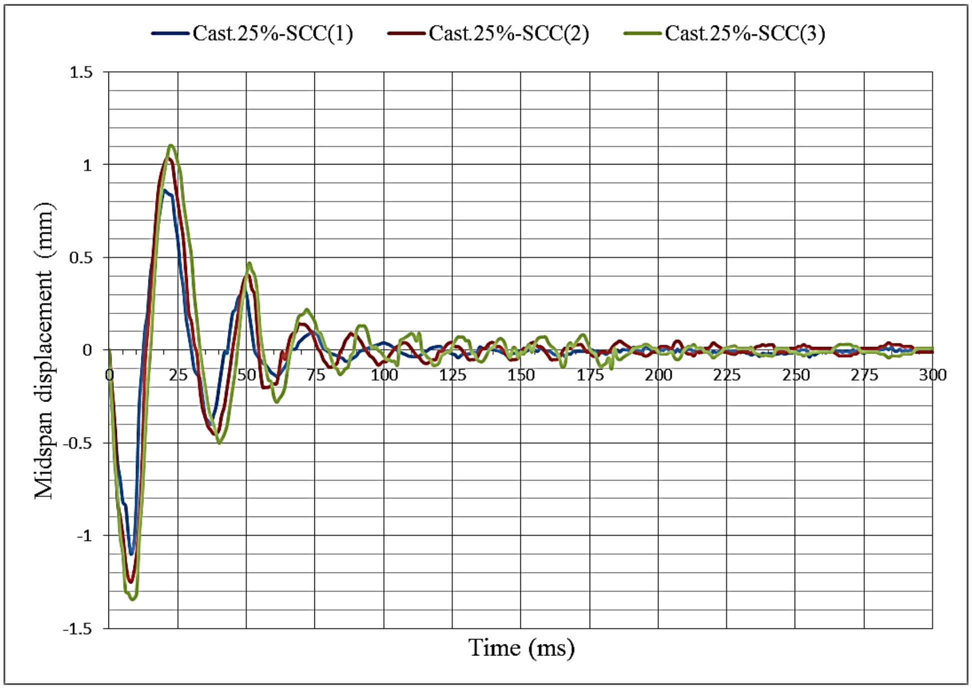

Figure 7. Displacement –History of Composite Castellated Beam 25%

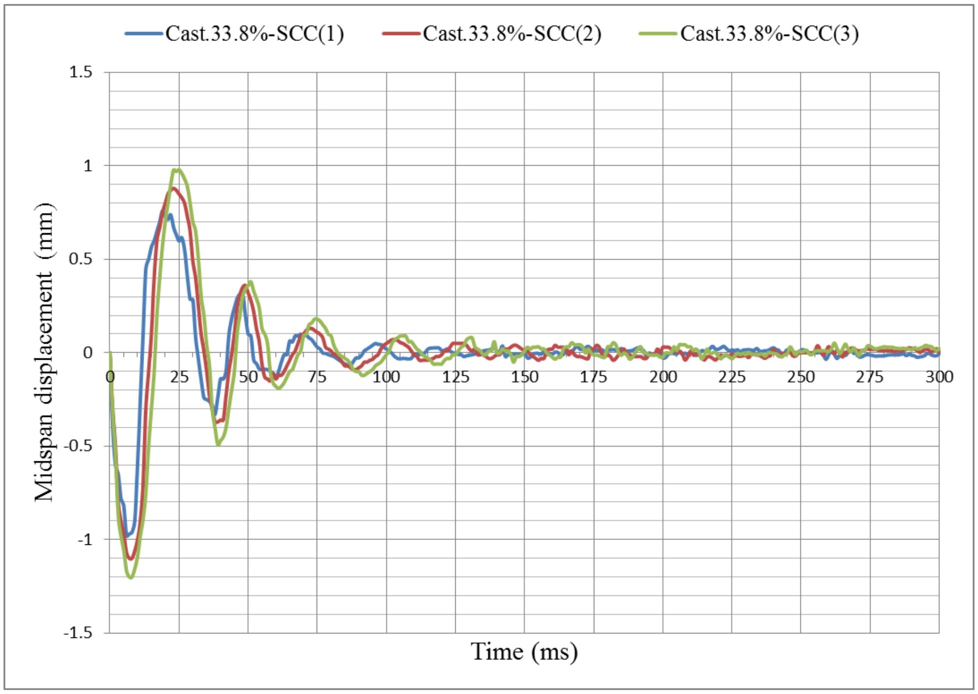

Figure 8. Displacement –History of Composite Castellated Beam 33.8%

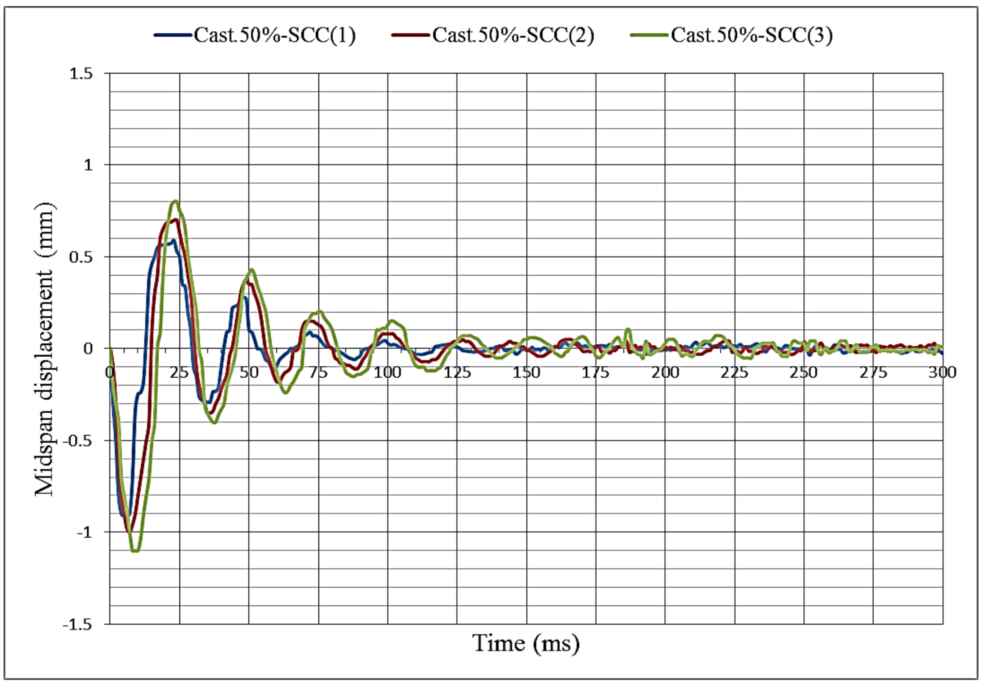

Figure 9. Displacement –History of Composite Castellated Beam 50%

3.2. Force History

Each specimen was tested under the effect of falling the steel ball weighs 7.0 kg from a distance 1.5 m. Figures 10 to 13 show the force response of specimens under consideration. The overall force response behavior of the tested beams introduced that the force increased dramatically in the first cycle of vibration to give the maximum amplitude of impact force in the transient response, then it takes many cycles before it dampens and the vibration vanished. The maximum impact load increased slightly with the increase of the degree of castellation for all specimens by a percentage not exceed 16.13%, it may be attributed to the increasing of beam stiffness as the degree of castellation adopted in the present study increased. This percentage of increasing may be considered rather slight but it is compatible with the amount of mass of the falling steel ball.

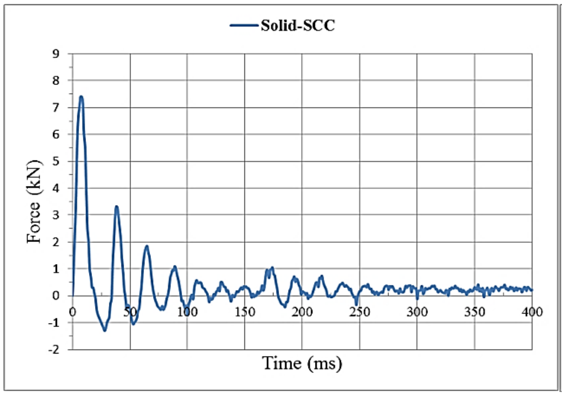

Figure 10. Force–History of Solid Composite Beam

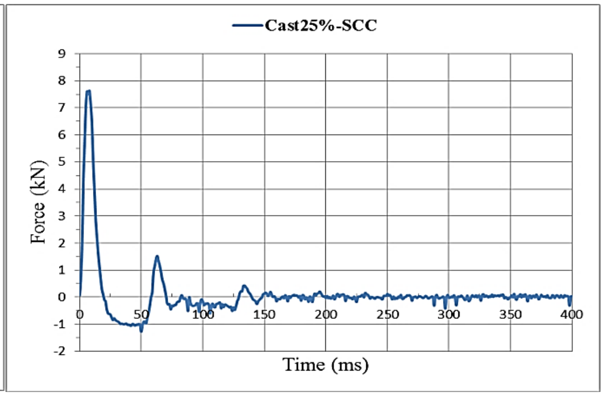

Figure 11. Force–History of Composite Castellated Beam 25%

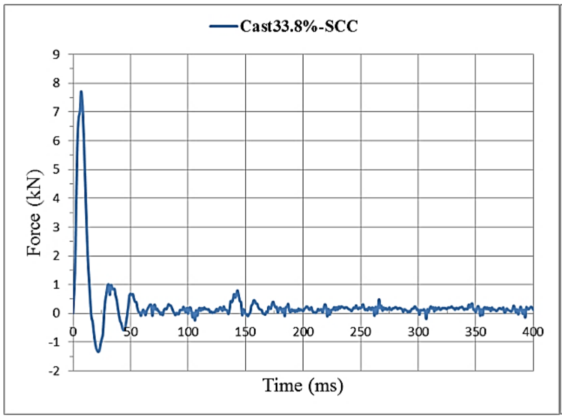

Figure 12. Force–History of Composite Castellated Beam 33.8%

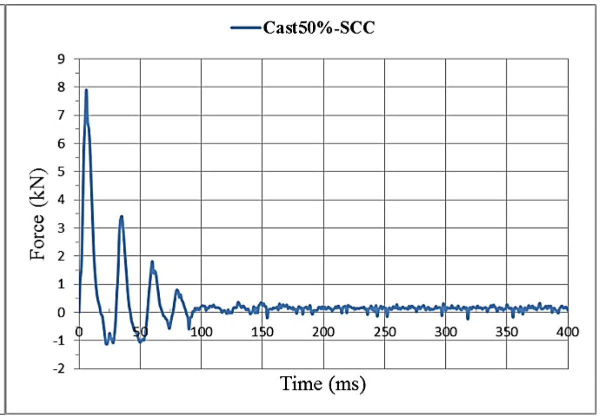

Figure 13. Force–History of Composite Castellated Beam 50%

3.3. Crack Patterns

3.3.1. Solid composite beam (λ=0%)

After falling of steel ball for the first time there was a little surface crushing. While after the second strike, longitudinal and transverse cracks on the top surface appeared and its width was 0.025 mm, in addition to vertical cracks on both sides of transverse axis have a width 0.01 mm. Followed by vertical side cracks on both ends of the beam after the third strike. Plate 3 shows the crack pattern after the first, second and third strike.

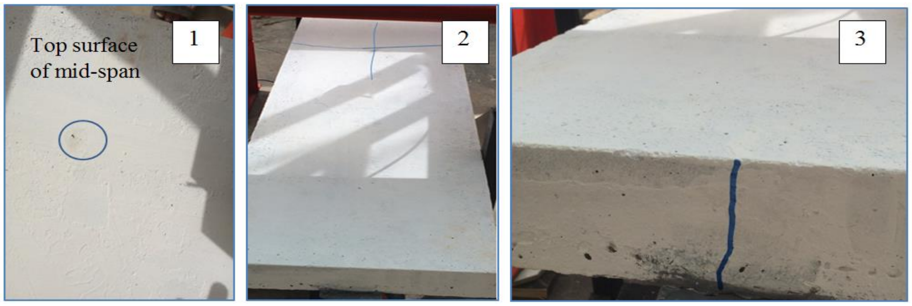

Plate 3. Crack Patterns of Solid Composite Beam

3.3.2. Composite castellated beam (λ=25%)

Orthogonal cracks on the top surface of midspan were appeared after the first strike, its width was about 0.015 mm. In addition to vertical crack at each transverse side, its width was 0.02 mm. After the second strike, these old cracks became little wider and the current width is 0.025 mm. Whereas after the third strike transverse crack at the bottom surface of midspan was created and its width was 0.01 mm, most of these can be noticed in Plate 4.

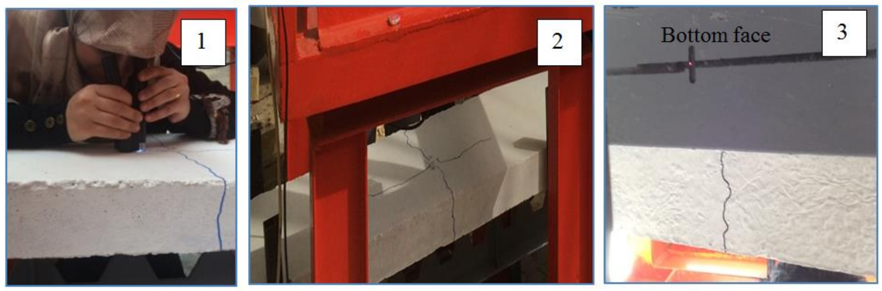

Plate 4. Crack Patterns of Composite castellated beam 25%

3.3.3. Composite castellated beam (λ=33.8%)

Longitudinal and transverse crack at the top surface of midspan appeared after the first strike where its width was 0.015 mm. The width of these cracks increased and became 0.04 mm after the second strike, in addition to appearing transverse crack in the bottom surface of midspan its width was 0.025 mm. A vertical crack at the longitudinal end at both ends its width was 0.025 mm created after the third strike, in addition to increasing the width of bottom surface cracks to be 0.04 mm, See Plate 5.

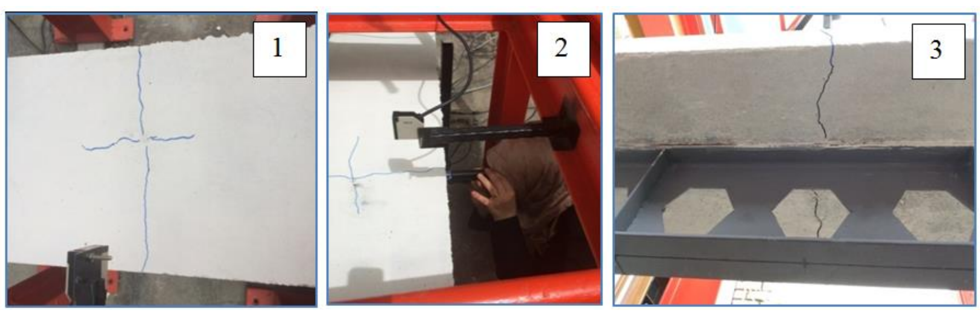

Plate 5. Crack Patterns of Composite castellated beam 33.8%

3.3.4. Composite castellated beam (λ=50%)

Orthogonal cracks formed after the first strike on the top surface of midspan its width 0.025 mm, in addition to vertical cracks at both transverse sides its width 0.04 mm. After the second strike, the old cracks on the top surface have extended where its width is 0.025 mm. The width of old cracks on top surface became 0.04 mm after the third strike, and generated new inclined crack on the top surface its width was 0.015 mm. Also vertical cracks appeared on both ends its width 0.015 mm. Plate 6 shows most of the previous stages.

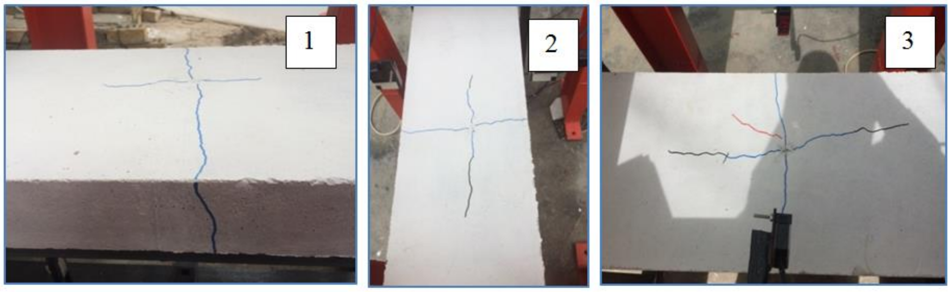

Plate 6. Crack Patterns of Composite castellated beam 50%

4. Conclusions

From this experimental study the following conclusions were drawn:

1. The overall force response behavior of the tested beams introduced that the force increased dramatically in the first cycle of vibration to give the maximum amplitude of impact force, then it takes many cycles before it dampens and the vibration vanished.
2. The maximum impact load increased slightly with the increase of the degree of castellation for all specimens by a about 16.13%. This percentage may be considered rather slight but it is compatible with the kinetic energy i.e. the height and the magnitude of falling mass.
3. The sequent strikes caused increasing the maximum amplitude occurred had been recorded of the displacement history. The percentages of amplitude increasing after the third strike compared with the effect of first strike were about 23%.
4. It can be noticed that as the degree of castellation increases the time required to settle down decreased, i.e. the fluctuation of displacement is damped quickly. Also, the amplitudes of vibration decreased as the degree of castellation increased, where the percentage of decrease depending on the solid specimen were 3.51%, 14.04% and 20.18% for the degrees of castellation 25%, 33.8%, and 50% respectively.
5. The width of cracks did not exceed 0.025 mm in all specimens after the first strike.
6. After the third strike, the width of cracks reached about 0.1mm for specimens have solid steel I-section, whereas specimens which have castellated steel I-section reached to less than this amount, which was 0.04mm, which refers to enhancing the performance of the beams by castellation process.

5. References

[1] A. R. Galambos, M. U. Hosain, and W. G. Speirs, "Optimum expansion ratio of castellated steel beams," *Eng. Optim.*, vol. 1, no. 4, pp. 213–225, 1975.

[2] H. Saito *et al.*, "Loading capacities and failure modes of various reinforced-concrete slabs subjected to high speed loading," *Nucl. Eng. Des.*, vol. 156, no. 1–2, pp. 277–286, 1995.

[3] J. D. Megharief, "Behavior of composite castellated beams." M.Sc. Thesis, Department of Civil Engineering and Applied Mechanics, McGill, 1997.

[4] A. S. Shaikh and P. B. Autade, "Structural Analysis and Design of Castellated Beam in Cantilever Action," 2016.

[5] Sh. Q. Abdulridha, H. H. Muteb and S. Sh. Abdulqader, "Experimental Investigation of Structural Behavior of Composite Steel Concrete Beams Subjected to Impact Load," *Int. J. Civ. Eng. Technol.*, vol. 9, no. 7, pp. 633–641, 2018.

[6] A. C494, "Standard specification for chemical admixtures for concrete," *Annu. B. Am. Soc. Test. Mater. Stand.*, vol. 4, 2010.

[7] C. BIBM and E. ERMCO, "EFNARC (2005) The European guidelines for self-compacting concrete," *Specif. Prod. Use*.

السلوك الانشائي للعتبات المركبة من الخرسانة والفولاذ المعرش المعرضة للحمل الصدمي

شيرين قاسم عبد الله هيثم حسن متعب الدعمي سرمد شفيق عبد القادر

الخلاصة

تشمل الدراسة الحالية تصنيع العتبات المعرشة التي ترتبط بالخرسانة ذاتية الانصهار بواسطة وصلات ربط لدراسة سلوكها تحت تأثير الاحمال الصدمية. تم تنفيذ أربعة عتبات مركبة ومعرشة بدرجات مختلفة من التعريش هي 0% و25٪ و33,8٪ و50٪. تعرضت هذه العينات لحمل الصدمة الناتجة عن السقوط الحر للكرة الفولاذية.

تطلب اجراء الفحوصات المختبرية تصنيع جهاز خاص تم توصيله بمتحسسات مختلفة وتمت عملية برمجتها باستخدام برنامج Lab VIEW 2016. تم تسجيل ومناقشة معاملات مختلفة والتي تضمنت مخطط القوة مع الزمن ومخطط الانحراف مع الزمن للحزم التي تم اختبارها. زاد الحد الأقصى للحمل الصدمي مع زيادة درجات التعريش التي تم تبنيها بنسبة 16,13٪ تقريبًا. وقد انخفضت سعة الاهتزاز المتمثلة في الانحراف مع زيادة درجات التعريش بنسبة 3,51٪ و14,04٪ و20,18٪ لدرجات التعريش 25% و33,8% و50% على التوالي.

الكلمات الدالة: العتب المعرش، العتبات المركبة من الخرسانة والحديد، استجابة الانحراف، استجابة القوة، الحمل الصدمي، الخرسانة ذاتية الرص.