

OPTIMIZATION OF OPENING SIZE FOR CASTELLATED BEAM WITH SINUSOIDAL OPENINGS

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ABSTRACT

Castellated beams are generally provided with hexagonal and circular openings in the web portion. However, in view of structural applications, appropriate size and shape of openings in web are always a major issue of concern. Research work carried out in optimizing sizes of castellated beam with hexagonal openings have reported that castellated beams fail mainly by local failure modes and stress concentrations at opening edges. Castellated beams with sinusoidal openings offer better performance due to its increased area for stress distribution in addition to curved edges that causes smooth stress distribution. Few researchers have studied flexural behaviour of castellated beams with sinusoidal openings; however, optimization for size of such openings has not been reported so far.

The paper focuses on parametric study of castellated beam with sinusoidal openings for optimization of opening size. Finite element analysis (FEA) is carried out by Abaqus software and also by Eurocode for different opening sizes and results obtained is experimentally validated. Results show that, castellated beam with sinusoidal opening of size 0.55times the overall depth of beam gives better strength.

Keywords: castellated beam; cellular beam; finite element analysis; Abaqus; web openings; sinusoidal openings; optimization of web openings.

Received: 10 March 2015; Accepted: 21 June 2015

1. INTRODUCTION

Use of steel for structural purpose in structure is rapidly gaining interest these days. In steel structures the concept of pre-engineered building (PEB) is most popular due to its ease and simplicity in the construction. Pre-engineered buildings have very large spans but comparatively less loading. Generally, steel sections satisfy strength requirement but the

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difficulty is that, section have to satisfy serviceability requirement (i.e. deflection criteria in safety check). This necessitates the use of beams with greater depth to satisfy this requirement. Use of castellated beams is the best solution to overcome this difficulty [15]. The castellated or perforated web beam is the beam which has perforation or openings in its web portion. Generally, the castellated beams are with hexagonal (Fig. 1) or square or circular shaped openings. The beams with circular openings are called as cellular beams (Fig. 2) [1]. As a modification, in castellated beam with hexagonal opening, the corners of opening are made round so as to offer smooth stress transfer area to avoid stress concentration. The beams with such curved shaped openings are known as castellated beam with sinusoidal openings (Fig. 3) [4].

Use of castellated beam with hexagonal openings is very common in recent years because of the simplicity in its fabrication. Castellated beams are fabricated by cutting flange of a hot rolled steel I beam along its centerline and then welding two halves so that the overall beam depth gets increased for more efficient structural performance against bending [5]. Castellated beams with hexagonal openings and circular openings have found widespread use, primarily in buildings, because of great savings in materials and construction costs. The research studies report that, use of beams with hexagonal openings require smaller amount of steel material and it is also superior to cellular beams from the cost point of view [6].

1.1 Types of castellated beam

Castellated beams are generally classified on the basis of type or shape of perforations made in the web of beam. Based on the shape of the opening the various types of castellated beams are shown in Fig. 1 to Fig. 3 [1].

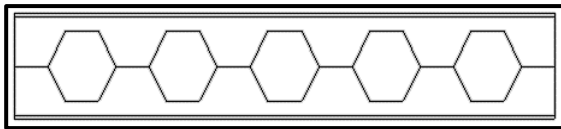


Figure 1. Hexagonal Castellated Beam

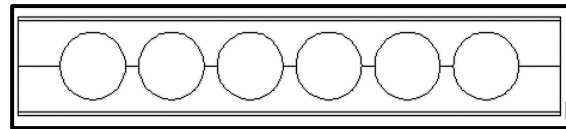


Figure 2. Cellular Beam

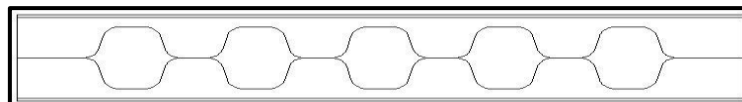


Figure 3. Castellated Beam with Sinusoidal Shaped Opening

1.2 Terminology in castellated beam

The various basic terms involved in the analysis and design of castellated beams are illustrated in Fig. 4, adopted from [9].

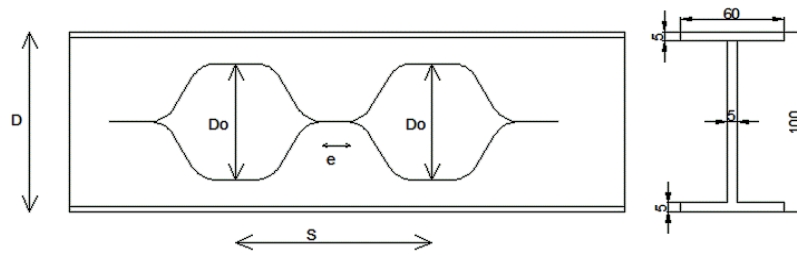


Figure 4. Typical cross section of the beam

Various dimensional parameters involved in the castellated beam with sinusoidal openings (Fig. 4) are defined as given below:

- D_o = Depth of opening provided.
- D = Overall depth of the opening.
- S = C/C spacing between the two opening
- e = Clear distance between two opening
- b = Width of flange of I beam
- t_f = Thickness of flange of I beam
- t_w = Thickness of web of I beam

2. REVIEW OF PREVIOUS STUDIES

In recent times, a lot of research work has been carried out for analysis and design of castellated beams, especially with hexagonal openings. There is no universally accepted design method for castellated beam because of complexity in geometry accompanied by complex mode of failure [11]. At present, there are possibly six failure modes of castellated beam namely, formation of flexure mechanism, lateral torsional buckling, formation of Vierendeel mechanism, rupture of welded joint, shear buckling of web post and compression buckling of web post[14]. Various research studies carried out for analysis and design of castellated beams are presented in the following section.

2.1 Wakchaure and Sagade [14]

Researchers have studied the flexural behavior of steel I –shaped castellated beams with hexagonal openings. The beams were modeled for different depths of web openings by varying spacing (S) to opening depth (D_o) ratio (i.e. S/D_o). The analysis of castellated steel beams (I-shaped cross-section), is performed using finite element software package ANSYS14 with two point load and simply supported support condition. The deflection at center of beam and study of various failure patterns are studied. The beams with increase in depth are then compared with each other and with parent section for various parameters and for serviceability criteria. From the results, it is concluded that, the castellated steel beam behaves satisfactorily with regards to serviceability requirements up to a maximum web opening depth of 0.6 times the overall depth (D). Castellated beams have proved to be efficient for moderately loaded longer spans where the design is controlled by deflection.

2.2 Wakchaure, Sagade and Auti [13]

The experimental investigations have been carried out by the researchers to study the behavior of castellated beams under two point loading (four point bending) by varying depth of hexagonal openings (and hence the overall depth). The results indicate that beam with opening size of 0.6 times the overall depth (D) carries maximum load compared to other sizes of openings. Also, investigators have concluded that with increase in depth of opening, vierendeel failure of beam becomes predominant.

2.3 Soltani, Bouchaïr and Mimoune [11]

The researchers have prepared a nonlinear numerical model to obtain behavior of castellated beams with hexagonal and octagonal openings. Parametric study is also carried out by varying depth of openings with increments of 10mm. The numerical results are compared with the existing literature and validated with help of MSC/NASTRAN software. The failure patterns of beams with various sizes are also studied. It is concluded that, the castellated beam with octagonal openings are more susceptible to local failure of web post buckling than the castellated beam with hexagonal opening.

2.4 Erdal and Saka [5]

The researchers have studied the load carrying capacity of optimally designed castellated beam by varying number of holes and spacing. FEA of same beams is also carried out by applying central point load and failure patterns are studied and verified using ANSYS. Study shows that, even though the members are relatively of shorter spans, lateral supports are governing factor for the analysis of beams due to torsional buckling. It is concluded that, the beam fails in vierendeel mode when the load is applied above openings, while it fails in the web post buckling when load is applied in between space of the openings.

3. ANALYSIS AND DESIGN OF CASTELLATED BEAM AS PER EUROCODE 3

The materials presented in this section are based on Refs. [2, 3, and 8].

3.1 Guidelines for perforations in web

The perforations made in the web greatly affecting the structural performance of the beam. Therefore, it is essential to make some logical and practical considerations while providing perforations in the beam. Following are the general guidelines which are given by Eurocode and some of them are based on the field or practical considerations. These standards in web perforations can be changed or modified without affecting the structural performance of the beam. These guidelines are as follows;

$$1.08 < \frac{S}{D_o} < 1.5$$

$$1.25 < \frac{D}{D_o} < 1.75$$

$$D_o \leq 0.8 D$$

$$e \leq 0.4 D_o$$

$$\text{Width of end post} \geq 0.5 D_o$$

3.2 Design of castellated beam

In this section, design standards provided by Eurocode 3 for designing of castellated beam are illustrated.

3.2.1 Check for moment (flexural) capacity of the beam

In this check, we have to ensure that maximum moment induced in the beam due to external loads should be less than moment capacity of the upper and lower Tee.

$$M_u < M_{pTee} \quad (1)$$

$$M_{pTee} = A_{Tee} \times P_y \times z \quad (2)$$

Where,

M_u = Maximum moment induced in the beam as per loading conditions.

M_{pTee} = Moment capacity of the upper or lower Tee.

A_{Tee} = Area of upper or lower Tee.

P_y = Yield stress of steel.

z = Lever arm (Distance between the centroid of upper and lower Tee).

3.2.2 Check for shear capacity of the beam

Maximum vertical and horizontal shear induced in the beam due to external loading should be less than vertical and horizontal shear capacities of the beam respectively.

$$V_{Vmax} < P_v \quad (1)$$

$$P_v = 0.6 \times P_y \times A_v \quad (2)$$

$$V_{Vmax} < P_{vy} \quad (3)$$

$$P_{vy} = 0.6 \times 0.9 \times A_{wt} \quad (4)$$

$$V_{Hmax} < P_{vh} \quad (5)$$

$$P_{vh} = 0.6 \times P_y \times A_{mwt} \quad (6)$$

$$V_H = T_{i+1} - T_i \quad (7)$$

$$T = \frac{M}{z} \quad (8)$$

Where,

V_{max} = Maximum vertical shear.

H_{max} = Maximum horizontal shear.

P_v = Shear strength of castellated beam.

A_v = Shear area (shear area of whole cross section)

$$= (D - 2t_f) \times t_w \quad (9)$$

P_{vy} = Vertical shear capacity.

A_{wt} = Shear area of Tee

$$= (D - 2t_f - D_o) \times t_w \quad (10)$$

P_{vh} = Horizontal shear capacity.

A_{mwt} = Horizontal shear area

$$= e \times t_w \quad (11)$$

V_H = Horizontal shear.

T = Axial load at different point.

M = Bending moment at different point.

3.2.3 Check for flexural and buckling strength of web post

Flexural and buckling strength of web post should be checked by the empirical formula given below,

$$\frac{M_{max}}{M_e} < \left[C1 \left(\frac{S}{D_o} \right) - C2 \left(\frac{S}{D_o} \right)^2 - C3 \right] \quad (12)$$

Where,

M_{max} = Bending moment of critical web post section

$$= V_{hmax} \times \left(\frac{D_o}{2} \right) \quad (13)$$

M_e = Bending resistance of critical web post section

$$= \frac{t_w \times P_y \times (S - 2b)^2}{2} \quad (14)$$

$$C1 = 5.097 + 0.1464 \left(\frac{D_o}{t} \right) - 0.00174 \left(\frac{D_o}{t} \right)^2 \quad (15)$$

$$C2 = 1.441 + 0.0625 \left(\frac{D_o}{t} \right) - 0.000683 \left(\frac{D_o}{t} \right)^2 \quad (16)$$

$$C3 = 3.645 + 0.0853 \left(\frac{D_o}{t} \right) - 0.00108 \left(\frac{D_o}{t} \right)^2 \quad (17)$$

3.2.4 Check for Vierendeel bending of tee

Vierendeel bending moment of the lower or upper Tee should be less than the local bending resistance of respective Tee.

$$M_{pTeeLocal} = \frac{A_{Tee} \times P_y \times Z_{Tee}}{2} \quad (18)$$

$$M_{pv} = V_{max} \times l_{eff} \quad (19)$$

$M_{pTeeLocal}$ = Bending resistance of Tee of beam.

M_{pv} = Vierendeel bending moment.

l_{eff} = Effective length of opening.

Effective length of opening is depends on the type of opening provided.

$$\text{For Circular opening, } l_{eff}=0.45 \times D_o \quad (20)$$

For other opening l_{eff} is width of opening.

3.2.5 Check for fracture in welding

Strength of weld should be more than maximum horizontal shear force in the section,

$$\text{Shear strength of the weld} > V_{hmax} \quad (21)$$

$$\text{Shear strength of the weld} = \frac{e \times t_w \times P_y}{\sqrt{3}} \quad (22)$$

3.2.6 Check for deflection

Deflection of beam is calculated as per standard formulae for perforated depth of the beam. Additional deflection due to openings is calculated by adding 15% to 25% deflection in above calculated deflection.

4. METHODOLOGY ADOPTED FOR OPTIMIZATION OF OPENINGS

Following the design standards of Eurocode, the approach is decided to achieve objectives of the research. The analysis of the beam with sinusoidal shaped openings is carried out for different sizes and the optimized section is tested experimentally for the purpose of validation of the research.

4.1 Selection of method of analysis

In order to optimize the dimension of the openings of the castellated beam, it is very important to decide proper analytical method. Due to complex geometry of castellated beam the finite element analysis (FEA) is the best available method to analyse the beams. FEA of castellated beam under consideration is done by simulation software "Abaqus/CAE 6.13".

4.2 Selection of parameters for parametric study on beam with sinusoidal openings

Depending upon the limitations of opening specified by the codes, different dimension of the sinusoidal openings are selected. The parameter considered for the study is D/Do ratios and S/Do of the opening. The variations in the parameters and corresponding cross sectional

dimensions of the sinusoidal openings are given in Table -1. All the castellated beams have been derived from the 100 mm depth hot rolled steel (HRS) I section. The analysis of all the beams considering the parameters given in Table -1 are modelled and analysed in Abaqus software and the optimized section is found out. While varying the S/Do ratio for sinusoidal openings beam, it is observed that, as S/Do ratio reduces (from 1.4 to 1.2) the clear distance between two openings (i.e. 'e') goes on reducing. So beam is tended to fail in local failure of horizontal shear. For sinusoidal beams, first of all S/Do (i.e. 1.4) ratio is kept same while D/Do ratio is kept varying from 1.25 to 1.75. After this same process is repeated for all other S/Do ratio (i.e. for S/Do = 1.3 and 1.2).

Table 1: Parameters considered for sinusoidal shaped opening

Sr. No.	D (mm)	Do(mm)	D/Do	S/Do	S (mm)	e (mm)
1	140	80	1.75	1.4	112	22.65
2	145	90	1.61	1.4	126	22.09
3	150	100	1.5	1.4	140	26.36
4	155	110	1.41	1.4	154	32.12
5	160	120	1.33	1.4	168	38.05
6	140	80	1.75	1.3	104	14.34
7	145	90	1.61	1.3	117	14.66
8	150	100	1.5	1.3	130	16.69
9	155	110	1.41	1.3	143	17.08
10	160	120	1.33	1.3	156	23.2
11	140	80	1.75	1.2	96	7.06
12	145	90	1.61	1.2	108	7.04
13	150	100	1.5	1.2	120	9.95
14	155	110	1.41	1.2	132	10.1
15	160	120	1.33	1.2	144	11.94

4.3 Failure criteria

In order to decide the failure of the beam in Abaqus, Von-misses failure criteria has been used. The criteria states that, failure of the structure would take place if the von-misses stresses in the structure reaches to the value of yield stress of the material. Thus, in the present work, as steel is the material used for beams and yield stress of steel is 250 N/mm^2 and hence the load corresponds to yield stress of steel is taken as permissible load.

5. FINITE ELEMENT ANALYSIS OF CASTELLATED BEAM WITH SINUSOIDAL OPENINGS

FEA of all castellated beams is carried out in Abaqus software to determine the optimum section which fails at greater load.

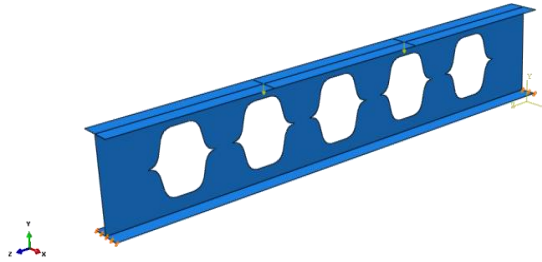


Figure 6. FE model of castellated beam

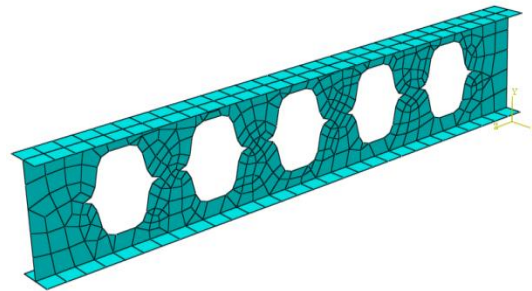


Figure 7. Meshing of castellated beam

FE model of one of such castellated beams with sinusoidal openings is shown in Fig. 6 along with loading and boundary condition. The beam is modelled as 3D shell element and the meshing of model is shown in Fig. 7. Quad-dominated S4R doubly curved element is used for meshing purpose. The various dimensions of openings along with their loads at yielding, deflections by FEA and their respective stresses for yield load are given in Table 2. for sinusoidal shaped openings [7].

Table 2: Results of FEA of castellated beam with sinusoidal openings

Sr. No.	Do	D	D/Do	S/Do	Length of Opening	Load at Yield(kN)	Deflection by Software (mm)	Stresses (N/mm ²)
1	80	140	1.75	1.4	89.35	31	1.468	252.913
2	90	145	1.61	1.4	103.91	32	1.309	257.845
3	100	150	1.5	1.4	113.64	32	1.515	251.9
4	110	155	1.41	1.4	121.88	34	1.594	251.03
5	120	160	1.33	1.4	129.95	30.6	1.914	259.026
6	80	140	1.75	1.3	89.66	29.3	1.287	257.242
7	90	145	1.61	1.3	102.34	29.6	1.291	255.771
8	100	150	1.5	1.3	113.31	30.6	1.402	253.179
9	110	155	1.41	1.3	125.92	31	1.353	251.461
10	120	160	1.33	1.3	132.8	29.7	1.59	259.808
11	80	140	1.75	1.2	88.94	14.1	0.584	250.564
12	90	145	1.61	1.2	100.96	14.9	0.614	253.944
13	100	150	1.5	1.2	110.05	21	0.85	251.262
14	110	155	1.41	1.2	121.9	25	1.155	252.25
15	120	160	1.33	1.2	132.06	23	1.03	254.123

From the result of this analysis it is observed that the beam with depth of opening 0.55 times its overall depth behaves satisfactorily in respect of load carrying capacity (32.2kN). In the other words beam with D/Do ratio of 1.41 and S/Do ratio of 1.4 gives more satisfying results than the other. The variation in failure load against the depth of opening is illustrated in graphical format in Fig. 8. While Fig. 9 and Fig. 10 show the variation in stress (maximum 251.03 N/mm²) and deflection (maximum 1.594 mm) respectively for optimized castellated beam with sinusoidal shaped opening. This optimized beam is highlighted in above Table 2.

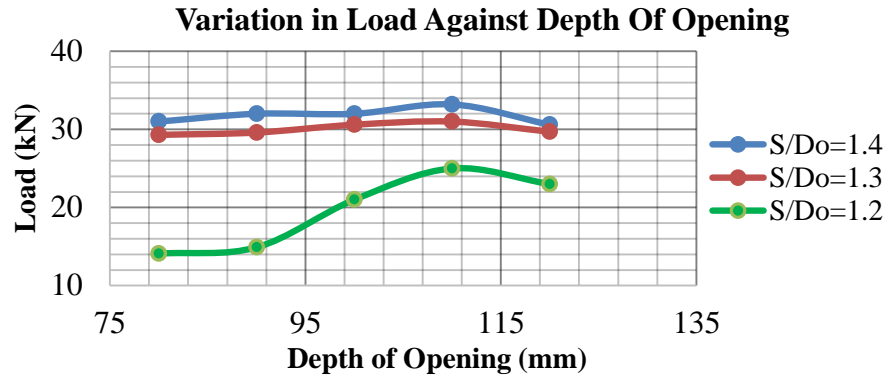


Figure 8. Variation in yield load for different S/Do and D/Do ratio for sinusoidal opening

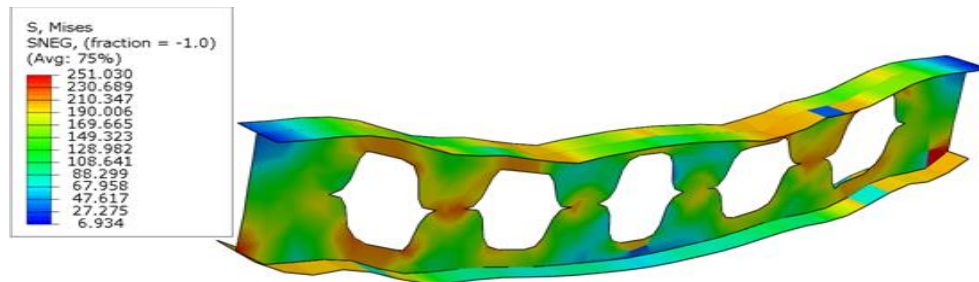


Figure 9. Variation in stresses of optimized castellated beam with sinusoidal openings

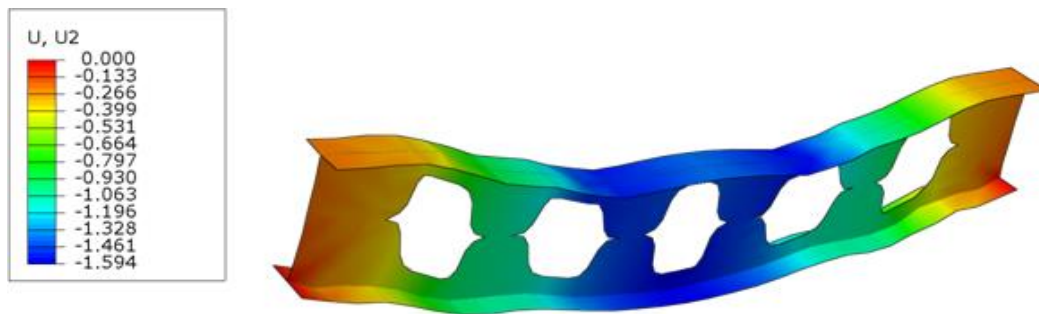


Figure 10. Deflection of optimized castellated beam with sinusoidal openings

6. EXPERIMENTAL VALIDATION OF OPTIMIZED BEAM

Optimized beam which are obtained by finite element analysis are fabricated and tested in the laboratory under the two point loading applied by universal testing machine (UTM) of capacity 600 kN. The test setup for both the optimized castellated beam with sinusoidal opening is shown in Fig. 11. Deflection is measured at centre by using dial gauge. The results of these tests are given in Fig. 12 graphical form by load vs. deflection curve.

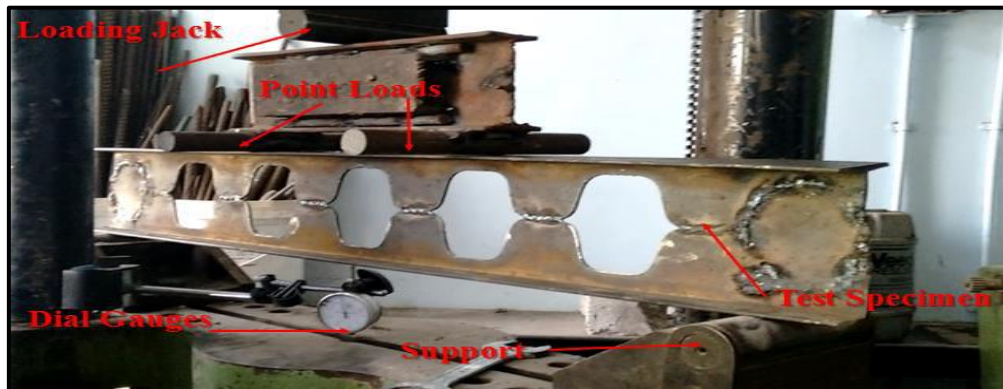


Figure 11. Test setup for both the optimized castellated beam with sinusoidal opening

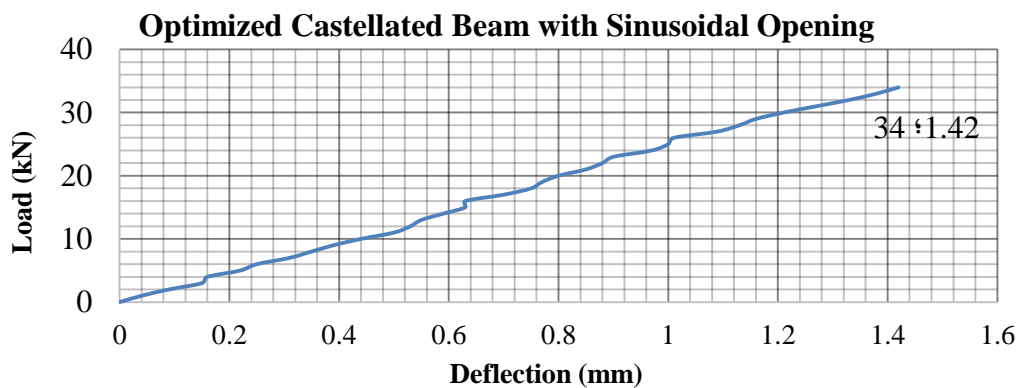


Figure 12. Load vs. deflection curve for optimized castellated beam with sinusoidal opening

From above graphs, it is observed that optimized beam with sinusoidal opening takes the load of 34kN causing the deflection of 1.42 mm.

7. COMPARATIVE STUDY OF CASTELLATED BEAM WITH CIRCULAR AND DIAMOND SHAPED OPENING

After finding out optimized dimension for sinusoidal shaped castellated beam it is very important to choose the optimized shape for openings. In order to find out optimized shape comparison of results of hexagonal and sinusoidal shaped openings need to be done. This comparison of results of castellated beam with hexagonal and sinusoidal shaped openings is given in Table 3. Below;

Table 3: Failure load and deflection of castellated beam with type of openings

Sr. No.	Type of castellated beam (shape wise)	Failure load by von-misses criteria (kN)	Deflection by FEA (mm)	Deflection by experiment (mm)
1	Hexagonal opening [13]	30	1.3	1.36
2	Sinusoidal opening	34	1.594	1.42

From Table 3, it be concluded that castellated beams with sinusoidal shaped openings is more reliable from strength requirement point of view. In the other words, the castellated beam with sinusoidal shaped opening with D/Do ratio of 1.41 and S/Do ratio of 1.4 gives more satisfying strength results than the other shapes and sizes of castellated beam.

8. CONCLUSIONS

Following conclusions can be drawn from the study:

1. Castellated beam with sinusoidal openings of size of 0.55 times its overall depth with S/Do ratio of 1.4 and D/Do ratio of 1.41 of takes maximum load of 34 kN.
2. As in case of sinusoidal shaped openings more shear transfer area is available, therefore castellated beam with sinusoidal openings proves to be better than the other shaped openings in respect of taking loads.
3. Sinusoidal openings gives the curved edges instead of corners. Therefore, the stress distribution near the corner portion of opening is uniform resulting in less stress concentration at opening.
4. Results of Abaqus software (FEA) are in good agreement with the results of experimentation and also with method of analysis given by Eurocode.

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