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RESEARCH ARTICLE

Effect of Horizontal Distance of Web Opening on the Ultimate Load Carrying Capacity of Castellated Steel Beams by an Analytical Approach

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Abstract

Objectives: The primary objective of this current research is to determine the ideal horizontal spacing for hexagonal web openings and their maximum load-bearing capacity through Finite Element Analysis (FEA). **Methods:** The ISMB150 was implemented as a cross-sectional profile to fabricate distinct models of castellated beams with heights of 225 mm. The height of the web openings remained constant at 150 mm for the castellated beam model. The entire analysis is being done on ANSYS 19.2. **Findings:** The analysis has revealed that, for castellated beams with shallower depths, an optimal horizontal spacing of 44.9 mm for the web openings yields an ultimate load-bearing capacity of 144.26 KN. The results of castellated beams are measured in terms of ultimate load-carrying capacity, span-to-deflection ratio, load density, failure location, span-to-beam depth ratio, and the ratio of horizontal distance of opening-to-opening depth. **Novelty:** This research contributes analytical findings for the ideal horizontal distance of hexagonal web opening through maximum load-bearing capacity. Castellated beams have gained immense popularity within the structural engineering community today due to their visually appealing design featuring a variety of web-opening shapes. The primary objective of this current research is to determine the ideal horizontal spacing for hexagonal web openings and their maximum load-bearing capacity through Finite Element Analysis (FEA). The ISMB150 was implemented as a cross-sectional profile to fabricate distinct models of castellated beams with heights of 225 mm. The height of the web openings remained constant at 150 mm for the castellated beam model. The analysis has revealed that, for castellated beams with shallower depths, an optimal horizontal spacing of 44.9 mm for the web openings yields an ultimate load-bearing capacity of 144.26 KN. The results of castellated beams are measured in terms of ultimate load-carrying capacity, span-to-deflection ratio, load density, failure location, span-to-beam depth ratio, and the ratio of horizontal distance of opening-to-opening depth. This research contributes valuable insights into optimizing the design of castellated beams for enhanced structural performance. Further exploration and validation could provide additional refinements and applications in structural engineering.

Keywords: Horizontal distance of web opening; Number of openings; Ultimate load carrying capacity; Failure modes; ANSYS; Castellated beams

1 Introduction

The Steel beams with different types of shapes in the web opening are called castellated beams[1]. Web opening shape has been very popular since the beginning of the castellated beams era. The castellated beams have a gorgeous appearance because of the various opening shapes in the web[2]. The Castellated Steel Beams (CSBs) are generally used over larger spans for taking higher loads[3]. The general design process to select Castellated Beams (CBs) is based on their load-carrying capacity for a given load and span[4]. Cutting and welding are easier because of the development of the mechanized process for various shapes in the web opening[5]. Due to the advanced mechanized process today the use of castellated beams is very widespread in the industrial as well as in the private sector[6]. To satisfy the requirements of users the castellated beams are fabricated for any spans and depths[7]. Castellated beams have a higher strength to stiffness ratio as compared to solid beams. Castellated beams are fabricated for various shapes in the web opening like hexagonal, sinusoidal, octagonal, oval, rectangular, circular, capsule, diamond, etc., and in combination also. The main reason behind the popularity of castellated beams is the various shapes in the web opening, the same weight, and higher depth than parent beams[8]. Castellated beams have more aesthetic values when the faces of buildings are exposed to nature[9]. For the fabrication of castellated beams, Hot-rolled steel I-section is used[10]. The web is cut laterally with a definite design pattern and then shifted into two halves and re-welded together resulting in an increase in depth. The depth of castellated beams is 50% deeper, which is 1.5 times more depth than the parent section as shown in Figures 1, 2 and 3.

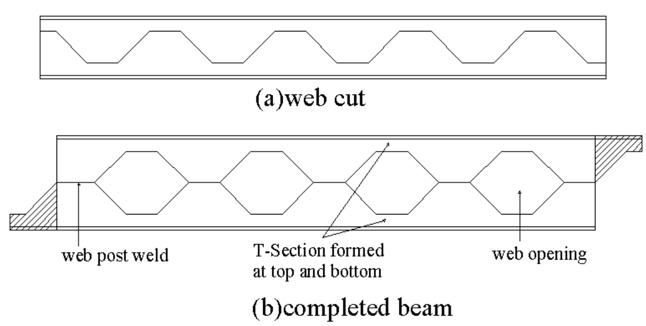

Fig 1. Castellated steel beam IC225

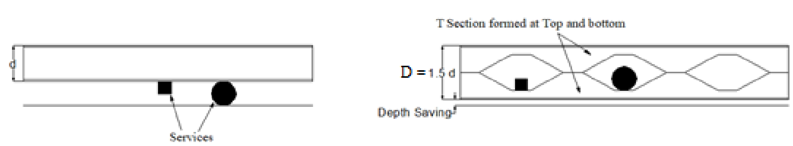

Fig 2. Web opening is utilized for the passing of services within the structural depth IC225

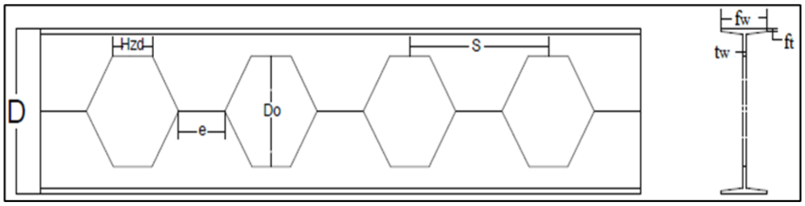

Fig 3. Typical cross-section of the castellated beam

Because of the increased depth of the section, the principal advantage of castellated beams is to increase the load-carrying capacity and deflection control by keeping the weight the same [11]. Web opening is utilized for passing different types of services within the structural depth and various dimensional parameters involved in the castellated beam with the hexagonal opening as shown in Figure 4 are defined as:

D = Overall depth of the castellated beam, D_0 = Depth of opening provided, Hzd = Top or bottom horizontal distance of opening, S = Pitch or C/c distance of opening, e = Clear distance between two openings, fw = Flange width of I beam, ft = Flange thickness of I beam and tw = Web thickness of I beam. In this research for the selected depth of castellated beams, Hzd = e.

The first noteworthy contribution in the field of castellated beams was made by Boyar (1964). The various modes of failure associated with castellated beams because of web opening and welds are Vierendeel mechanism formation, lateral-torsional buckling of web post, web post rupturing due to welded joints, entire span torsional buckling, flexural mechanism, buckling of the web post, etc. It was concluded that for plain webbed beams, the lateral-torsional instability and formation of failure mechanism may be handled by adopting the proper established method. Many researchers have studied the load, deflection, optimization of the web opening pattern, effect of stiffeners, and hybrid castellated beams. Researchers, predicted failure loads of castellated beams with hexagonal openings by using an artificial neural network. Simply supported beams with various modes of failure developed due to applied central point load, UDL(Uniformly Distributed Load), two-point loads which have acting symmetrically with respect to the centre line of the beam span. It is clear that a neural network provides an efficient alternative method for predicting the failure load of castellated beams.

a

b

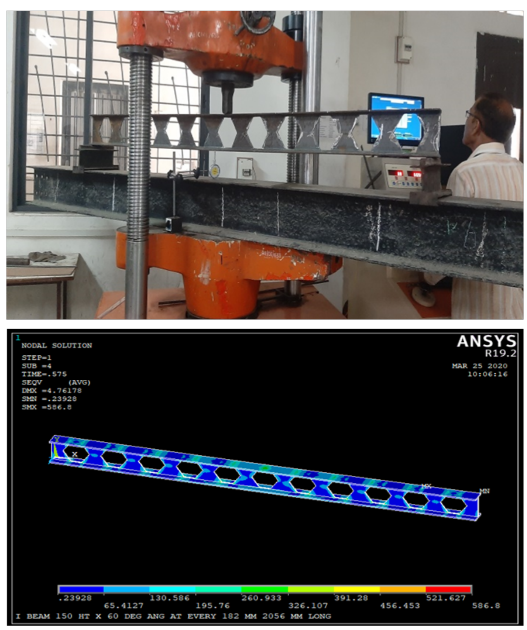

Fig 4. Experimental trial testing and ANSYS result for the trial-tested castellated beam

After studying the existing literature, it was found that very few papers address the issue of ideal horizontal spacing of hexagonal web openings for castellated beams experimentally and analytically. So here the attempt is being made to find the ideal horizontal spacing of hexagonal web opening with two variables like Hzd of web opening and numbers of the slot. The depth of the castellated beam is considered as 225 mm. The results of castellated beams are measured in terms of ultimate load carrying capacity, span to deflection ratio, load density, failure location, span to beam depth ratio and the ratio of horizontal distance of opening-to-opening depth, etc.

In this paper, more emphasis is given to hexagonal web opening castellated beams with two variables like Hzd of web opening and numbers of the slot.

2 Methodology

2.1 Methodology of Castellated Beam

Many times longer span beams are required in the construction of steel buildings where the loads are significant but because of this long span, the solid steel beam tends to deflect more[12–14]. In this condition, the castellated beam is an appropriate solution. In such cases, this method is proved economical as no extra material is required, however skilled labours are required for cutting and welding but their cost is reasonably low compared to extra material cost.

This paper includes testing and analysis of castellated steel beams for validation purposes. The beams having simply supported boundary conditions were set up in the loading assembly of UTM with enough care taken to make sure that the specimens were properly positioned in the loading assembly and the load point was exactly positioned at L/2 distance from both supports. The position of the dial gauge is at the centre of the span. The section was fully loaded up to permissible yield stress by the application of gradually increasing load, and the same procedure was repeated for every section. Only one dial gauge was installed for measurement of vertical deflection placed at L/2 distance, i.e., at the centre of the span section. After the yield load was reached, load application was stopped and unloading was done the dial gauge showed zero reading hence it indicates that the specimen regains its initial position. The yield load and the corresponding deflection were noted. Care should be taken at the time of testing that the position of applied load and support provision made is on the solid part of the web as far as possible. The experimental and ANSYS results are nearly the same and hence the results are validated. This is an important step to find out the results of solid as well as castellated beams of depth 225 mm by using ANSYS. The validation of experimental and analytical work on a sample basis is shown in Table 1.

Table 1. Experimental and analytical work

Sr	Depth of castellated Beams (mm)	Number of openings	Length of castellated Beam (mm)	Deflection (mm)	
				Experimental	Analytical
1	225	11	2056	4.93	4.76

The various design parameters are worked out from the basic properties of the ISMB 150 mm solid section to convert into castellated beams of depth, 225 mm. Hence, all the design parameters of the castellated beams are worked out in detail and depicted in Tables 3 and 4. Finally, to achieve the ultimate load capacity of castellated beams in terms of Hzd of opening, a number of slots, deflection, and stress are workout. Therefore, in this research, all the guidelines of castellated beams, as well as the process of fabrication, are followed. This output is very important for the designer because up till now, castellation means increases the depth of beams 1.5 times more than the parent or solid beams. But by varying the offset distance it is possible to build castellated beams of smaller depths as well as the span that satisfy the requirements of the industry or common users**.**

- **Detailed Finite Element Analysis**

For analytical modelling in ANSYS, 3-D modelling of solid structures SOLID 185 element is used. It is well-defined by 8 nodes having 3 DOF at every node: that is translation along x, y and z directions. The element has hyper elasticity, plasticity, creep, stress stiffening, large strain, and large deflection capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elasto-plastic materials, and fully incompressible hyper elastic materials. It is available in two forms. Homogeneous structural solid and two Layered structural solid It allows for tetrahedral, prism, and pyramid degenerations when used in irregular regions. The properties of the material used for the analysis are presented as below:

Steel (solid 185) having density 7850 kg/m^3, elasticity 2.1x10^5 MPa, Poison's ratio 0.30. The FE model with the meshing size 1 mm for castellated steel beams is shown in Figures 5, 6 and 7. This analysis aims to find out maximum load-carrying capacity, stress, and displacement in the CSBs by using FE results analysis. Ultimate failure load of ANSYS for 12 number of openings and horizontal distance of opening (Hzd) 81.7 mm are noted for selected bottom flange node of castellated beams (depth 225 mm) along Y, Z direction as depicted in Table 2.

Table 2. Ultimate failure load of ANSYS

Sr.	Node Number	F_Y	F_Z
1	45107	7296.8	97.110
2	45109	7960.6	420.52
3	45110	8358.4	-167.10
4	45111	-2016.2	515.75
5	45112	-3640.8	266.82
6	45117	-7218.3	-211.86
7	45131	-7175.7	-258.92
8	45133	-5762.9	597.88
9	45135	1199.6	4706.5
10	45139	-3887.6	-34.548
Total values (N)		0.13311E+006	0.280807E-008

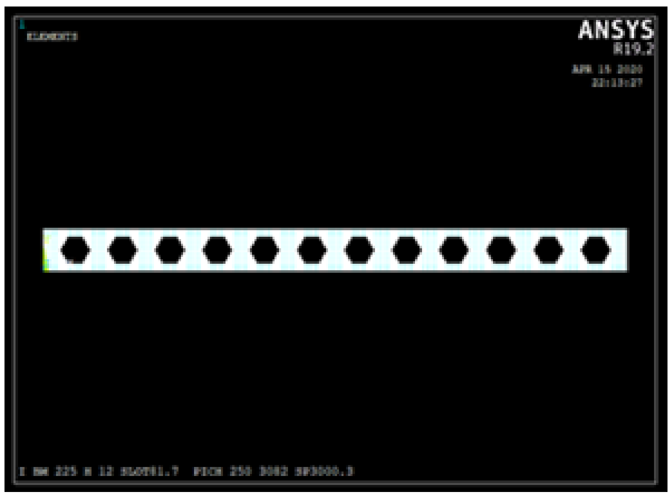

Fig 5. FE model of castellated beams with meshing size of 1 mm

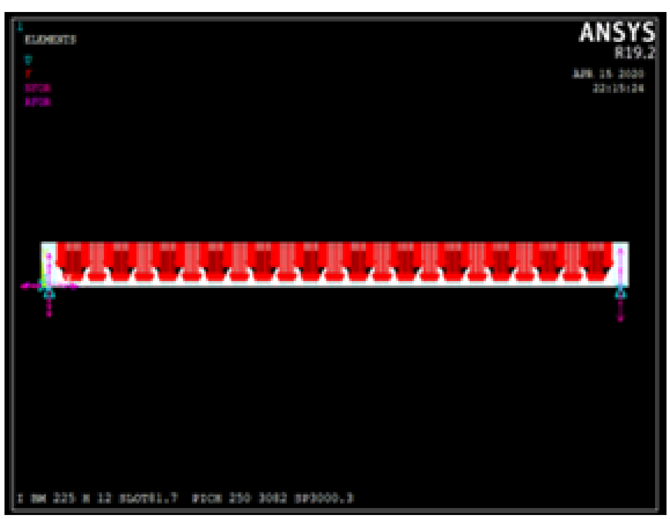

Fig 6. Castellated beams with the position of support and applied uniformly distributed static load

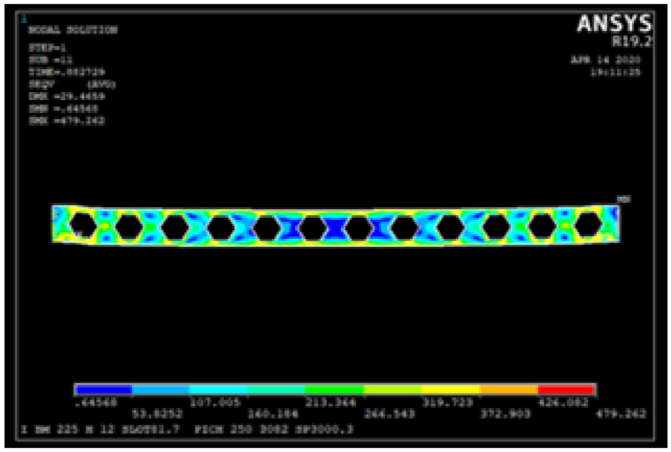

Fig 7. Castellated beam with maximum deflection

3 Results and discussion

The various design parameters are worked out from the basic properties of the ISMB 150 mm solid section to convert into castellated beams of depth, 225 mm. Hence, all the design parameters of the castellated beams are worked out in detail and depicted in Tables 3 and 4. Finally, to achieve the ultimate load capacity of castellated beams in terms of Hzd of opening, a number of slots, deflection, and stress are workout. Therefore, in this research, all the guidelines of castellated beams, as well as the process of fabrication, are followed. This output is very important for the designer because up till now, castellation means increases the depth of beams 1.5 times more than the parent or solid beams. But by varying the offset distance it is possible to build castellated beams of smaller depths as well as the span that satisfy the requirements of the industry or common users.

Table 3. A castellated beam of depth 225mm

fw mm	tw mm	ft mm	Height mm	H_1 mm	I_{X1} mm^4	R_1 mm	I_{X2} mm^4	Amm^2	A_{R2} mm^2	Total I_{XX} mm^4
75	5	8	150	134.0	1002543	71	6400	1200	6049200	7058143
75	5	8	200	184.0	2595627	96	6400	1200	11059200	13661227
75	5	8	225	209.0	3803887	108.5	6400	1200	14126700	17936987
Depth mm		I_{XX} mm^4	I_{XX} mm^4	Z_{XX} mm^3	0.9xZ_{XX} mm^3	Do mm		Of Set1 mm		Incline Distance mm
225		17936987	16143300	159439.9	143496	150		75		43.3

Table 4. Various parameters of castellated beams of depth 225 mm

S/N	Nos.of Slot	Hzd mm	S mm	Beam length mm	Span mm	Ult.Load N	Bending moment N-mm	Shear stress N/mm^2	Span/ Def.	Defl. mm	Load density N/mm	Failure location	Span/ D	Hzd/ Do
1	13	81.7	250	3332	3250	131470	53451399	372	98	33.21	40	L CORNER	14	0.54
2	14	72.8	232	3324	3251	131570	53424003	372	128	25.34	40	CENTER	14	0.49
3	15	65	217	3314	3249	132820	53942788	376	135	24.10	41	CENTER	14	0.43
4	16	58.3	203	3310	3251	133250	54154154	377	144	22.61	41	CENTER	14	0.39
5	17	52.3	191	3303	3250	133570	54270933	378	145	22.46	41	CENTER	14	0.35
6	18	47	181	3298	3251	132940	54021689	376	147	22.11	41	CENTER	14	0.31
7	19	42.2	171	3291	3249	133150	54077150	377	147	22.12	41	CENTER	14	0.28

Continued on next page

Table 4 continued

8	12	81.7	250	3082	3000	133110	49917264	348	102	29.46	44	R CORNER	13	0.54
9	13	72.1	231	3072	3000	141730	53149920	370	97	30.99	47	CENTER	13	0.48

3.1 Observations for castellated beams of 225 mm depth

The span-to-depth ratio is considered to create a constant span of the castellated beam and ultimate loads are compared. In this case, the depth of the beam is 225 mm. The starting ratio is 14 which has 13 openings and a pitch of 250 mm; the maximum Hzd of the opening is 81.7 mm. To achieve the constant span of 3250 more or less 1mm the Hzd is varied from 81.7 to 42.2 mm. Similarly, span/depth ratio 13 for 3000 mm, Hzd varied from 81.7 to 40 mm. As per Table 5, the last column shows the ratio of Hzd/Do. In this case, the opening is 150 mm and the second column of the table shows Hzd distance. The slot with a ratio of 0.54 failed at the ends and all others with a lower ratio failed at the center. 81.7 mm Hzd of the slots is good enough for the top portion of the slot to bend under the shear force and make the section fail. The two-section which failed at the center with maximum load has a ratio of 0.35 and 0.30 for Hzd 52.3 and 50.5 mm respectively; this means that for the slot of narrow width, the corner portion does not show failure in shear. The logic that the Hzd /Do ratio greater than 0.54 tends to fail at the corner. Or in other words, the Hzd distance of 81.7 mm is failing at the corner. The ratio in the second last column of the table is the span to depth ratio of beams, which is 225 in this case. So, the first case of horizontal distance equal to 52.3 mm fails at the centre. This is because the Hzd /Do ratio is 0.35. It is observed that the failure load is very high at 133.570 kN. In the second case, the last column Hzd /Do ratio is 0.30, Hzd is equal to 44.5mm, and failure load is 144.260kN. As the horizontal distance increases, the section fails at the corner at a lower load of 131 kN. This is the indication that this is the weaker portion of the castellated beam. As the load goes down, the failure pattern changes i.e. failure is observed at center. The narrow Hzd at the centre and wider at the end shows the reduction in failure load. This is because the bending moment, which it can withstand, is constant. Further, as we go down, the Hzd get decreases and up to the optimum value thereby load increases, and thereafter load decreases. The inference is much clear that the wider opening is not desirable. In the present study the angle of 60° therefore a smaller horizontal distance (Hzd) like 40, 45 mm is preferable. For depth 225mm of beams, the opening is 150 mm and hence the ratio of 0.35 and 0.30 works out to be the best for Hzd 52.3 mm and 44.9 mm having span 3250 and 3000 mm and ultimate loads 133.570 kN and 144.260 kN.

From Table 5, it is very clear that as the span increases the load-carrying capacity is reduced. The Hzd distance for 3250 a span is 52.3 mm and for span of 3000mm, the critical Hzd distance is 44.9 mm where the ultimate load carrying capacity enhances. For Hzd Distance 81.7 mm shows the same value of ultimate failure load as per Figure 4 **a** and **b**. As the load decreases further Hzd decreases and hence the load capacity increases up to the specific value. This is called the optimum value of Hzd beyond that load value decreases.

Table 5. Analytical representation of various parameters of castellated beams of depth 225 mm

S/N	Nos.of Slot	Hzd mm	S mm	Beam length mm	Span mm	Ult.Load N	Bending moment N-mm	Shear stress N/mm^2	Span/ Def.	Defl. mm	Load density N/mm	Failure location	Span/ D	Hzd/ Do
1	13	81.7	250	3332	3250	131470	53451399	372	98	33.21	40	L CORNER	14	0.54
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3	15	65	217	3314	3249	132820	53942788	376	135	24.10	41	CENTER	14	0.43
4	16	58.3	203	3310	3251	133250	54154154	377	144	22.61	41	CENTER	14	0.39
5	17	52.3	191	3303	3250	133570	54270933	378	145	22.46	41	CENTER	14	0.35
6	18	47	181	3298	3251	132940	54021689	376	147	22.11	41	CENTER	14	0.31
7	19	42.2	171	3291	3249	133150	54077150	377	147	22.12	41	CENTER	14	0.28
8	12	81.7	250	3082	3000	133110	49917264	348	102	29.46	44	R CORNER	13	0.54
9	13	72.1	231	3072	3000	141730	53149920	370	97	30.99	47	CENTER	13	0.48
10	14	63.8	214	3064	3000	143580	53843777	375	127	23.55	48	CENTER	13	0.43
11	15	56.7	200	3057	3000	143720	53896369	376	125	24.07	48	CENTER	13	0.38
12	16	50.5	188	3051	3000	143870	53952712	376	141	21.23	48	CENTER	13	0.34
13	17	44.9	176	3045	3000	144260	54099058	377	145	20.73	48	CENTER	13	0.30
14	18	40.0	167	3040	3000	143910	53967895	376	110	27.18	48	CENTER	13	0.27

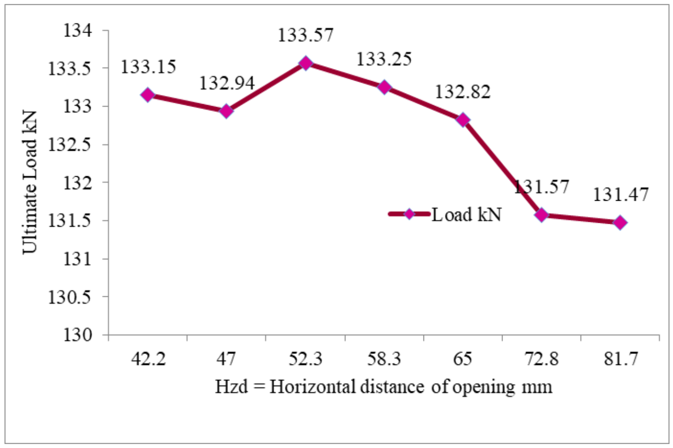

Fig 8. Ultimate load V/s Hzd of opening for the span 3250 mm of castellated beams 225 mm depth

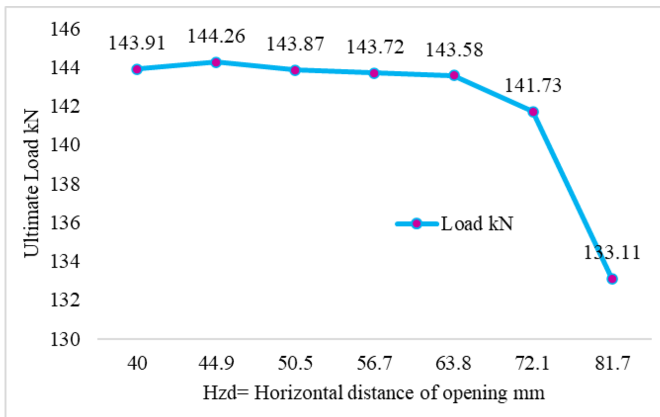

Fig 9. Ultimate load V/s Hzd of opening for the span 3000 mm of castellated beams 225 mm depth

4 Conclusion

The following conclusion is drawn from the analytical study of the castellated beams:

1. The ultimate load-carrying capacity of castellated beams is dependent upon the Hzd of the web opening.
2. As the Hzd distance of the opening increases beyond the specific value, the load carrying capacity of castellated beams decreases.
3. The failure modes of castellated beams are also dependent upon Hzd distance and the number of slots.
4. The castellated beams having a lower and higher Hzd distance of web opening fails at lesser loads at the support.

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