STATISTICAL ASSESSMENT OF CAPACITY PREDICTIVE MODELSOF CASTELLATED STEEL BEAMS

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ABSTRACT

Due to its unique properties contribute to efficient and visually appealing structure, castellated beams are used in various building types, including commercial, industrial, and institutional structures. Lot of strength predicting equations for castellated beams has been found in codes and literatures. These predicting equations are empirical and semi empirical in nature and the results are highly deviating from each other. The precision of such predictions is a great concern for the designers. Such deviation in the prediction needs to be addressed. About seven predicting equations proposed in various codes and literatures of various sources have been assessed through statistically based on 84 selective experimental data points. The deviation of the predicted strength of castellated beams as per the existing equations has been inferred. The strength predictions by Kerdal et al.[12] equation followed by AISC equation[1] are closely agreeable with the experimental results. The factors influencing the strength of castellated beams are still unsettled. The best predictions have been validated with the experimental result performed by us. A new model also has been proposed.

Keywords: Castellated Beam, Predictive Equation, Statistical tools, Experimental Database

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Introduction

A castellated beam is a structural component used in construction that is characterized by its distinctive shape. Castellated beams are typically made of steel and have a series of voids along their length. The manufacturing process of castellated beams involves taking a standard wide-flange beam and cutting it longitudinally along the web as shown in Fig. 1. The two halves of the web are then displaced vertically, usually in alternating fashion, to create the voids or cells. This process increases the beam's surface area while reducing its weight, resulting in a more efficient and lighter structural element compared to a solid beam of the same size.

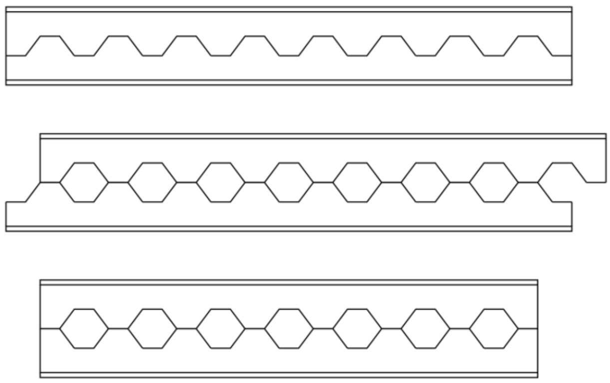


Fig. 1 Schematic Representation of process of a castellated beam

(**Source:** https://en.wikipedia.org/wiki/Castellated_beam)

The specific advantages of castellated beams includes weight reduction, Increased strength-to-weight ratio, Architectural appearance, Service integration such as electrical wiring, plumbing, and HVAC duct works. Castellated beams are commonly used in a variety of construction projects, including commercial buildings, industrial structures, sports arenas, and bridges. They provide a balance between structural efficiency, cost-effectiveness, and architectural appeal. However, they also have a few disadvantages such as reduced shear capacity, limited span lengths, increased deflection, Potential for increased fire risk. It is important to note that while castellated beams have these disadvantages, they are often dwarfed by the benefits they offer in specific applications[14].

As per AISC[1], the failure of castellated beams are primarily due to Compactness and Local buckling, Overall beam flexural Strength, Vierendeel bending of Tees, Web post buckling, Axial tension or compression, horizontal shear, Vertical Shear and Lateral Torsional Buckling[24]. The codes of practice and various literatures proposed empirical equations for estimating the strength of castellated beams. Since these equations are empirical, there has been a substantial difference in their forms. In view of this, the assessment of the accuracy of prediction of strength by these equations is necessary. Seven such equations have been assessed with 84 selected experimental databases on castellated beams.

1. Database

A significant research effort on castellated beams with diverse parametric studies has been carried out across the globe from the 1950s to the present day. The data about 84 experimental castellated beam used in this study has been taken from studies carried out by Research and Development swinden laboratories on 1957[18] and 1958[19], Toprac et al.

(1959)[25], Kolosowski, J. (1964)[13], Sherbourne (1965)[21], Sherbourne (1966)[22], Bazile et al. (1968)[5], Hosain et al. (1973)[9], Galambos et al. (1975)[8], Kerdal et al. [12] (1982), Okubo et al. (1985)[17], Zaarour et al. (1995)[22], Redwood et al. (1998)[20], Zirakian et al. (2006)[30], Wenting et al. (2018)[28]. The collected data are listed in Table 1.

Table 1 Geometric Details of Experimental Castellated beam Specimen

S. No.	ID	Author	fy (MPa)	D (mm)	b_f (mm)	t_w (mm)	t_f (mm)	S (mm)	L (m)	M (kNm)
1	A	The United Steel Co. Ltd., 1957. [18]	240	267	102	6	10	213	2.90	78
2	A2		240	267	102	6	10	213	2.90	89
3	A3		240	267	102	6	10	213	2.90	75
4	A4		240	267	102	6	10	213	2.90	85
5	A5		240	267	102	6	10	213	2.90	87
6	A6		240	267	102	6	10	213	2.90	89
7	1	The United Steel Co. Ltd., 1958. [19]	240	343	102	8	12	274	4.14	115
8	2		240	343	178	10	21	274	4.22	249
9	3		240	381	127	9	14	305	4.14	218
10	4		240	381	203	10	20	305	4.22	276
11	5		240	381	114	8	13	305	4.14	103
12	A1	Toprac, A. A. And Cooke, B. R.,. 1959. [25]	274	267	102	5	5	213	4.34	50
13	A2		274	300	100	5	5	240	5.48	58
14	A3		274	297	99	5	5	238	5.39	57
15	A4		305	296	100	4	5	237	5.65	61
16	a1	Kolosowski, J. (1964), [13]	300	457	127	13	9	61	4.20	226
17	E1	A. N. Sherbourne (1965). [21]	300	229	76	6	10	165	1.32	33
18	E2		300	229	76	6	10	165	1.32	25
19	E3		300	229	76	6	10	165	1.32	21
20	E4		300	229	76	6	10	165	0.82	12
21	1	Sherbourne, A. N., 1966[22]	282	229	76	6	10	183	3.99	59
22	2		282	229	76	6	10	183	3.92	58
23	3		282	229	76	6	10	183	4.13	61
24	1	Bazile, A. and Texier, J., 1968[5]	335	500	135	7	10	400	3.70	262
25	2		350	500	135	7	10	400	3.50	252
26	A1	Hosain, M. U. And Speirs, W. G., 1973[9]	446	381	102	6	7	584	3.51	157
27	A2		335	381	102	6	7	584	1.75	117
28	B1		335	381	102	6	7	400	1.60	123
29	B2		335	381	102	6	7	400	1.60	100
30	B3		335	381	102	6	7	400	2.40	117
31	G1		446	381	102	6	7	381	3.05	131
32	G2		319	381	102	6	7	254	3.05	134
33	G3		394	381	102	6	7	191	3.05	178
34	A1		300	381	102	5	8	305	1.20	112
35	A2		300	381	102	5	8	305	1.70	158

36	1	Galambos, A. R., Hosain, M. U. And Speirs, 1975[8]	300	303	101	6	7	242	1.00	105
37	2		300	355	101	6	7	284	1.30	122
38	3		300	341	101	6	7	272	1.20	119
39	4		300	403	100	6	7	323	1.30	117
40	A1	Kerdal et al. [12] 1982	293	609	140	7	11	144	1.90	325
41	A2		290	534	127	7	11	125	1.90	225
42	A3		291	458	127	7	11	124	1.90	170
43	A4		295	534	127	7	11	124	1.90	184
44	A5		286	609	140	7	11	146	2.02	241
45	A6		300	458	127	8	11	124	1.97	122
46	A7		310	534	127	7	11	125	1.97	142
47	A8		304	458	102	7	11	103	1.97	86
48	5SAB2	Okubo And Nethercot, [17]	290	524	124	7	11	376	0.75	53
49	5SAB4		290	524	125	7	11	376	1.51	104
50	5MAC4		295	525	124	7	11	376	1.50	105
51	5MAA2		295	524	124	7	11	378	0.76	45
52	5LAA2		296	526	128	7	11	376	0.75	49
53	5LAA3		296	527	125	7	11	380	1.14	66
54	6SAA2		293	606	146	7	11	382	0.76	53
55	6LAB2		277	606	145	7	11	445	0.89	64
56	6LAC2		277	605	143	7	11	444	0.89	56
57	6SAA1		293	604	144	7	11	443	0.44	25
58	4MAB2		291	451	124	8	11	440	0.88	60
59	4LAA2		297	450	123	8	11	435	0.87	61
60	4LAA4		297	452	124	8	11	433	1.73	123
61	4MAB4		291	452	124	8	11	436	1.74	122
62	4LAAA4		304	460	103	7	11	435	1.74	119
63	4LAAA2		304	460	103	7	11	453	0.91	60
64	10 1	Zaarour, Walid Jacques, 1995 [29]	357	371	70	4	4	256	3.05	60
65	10 2		357	418	70	4	4	255	3.05	45
66	10 3		357	376	71	4	4	370	3.05	56
67	10 4		357	425	71	4	4	372	3.05	38
68	12 1		312	476	78	5	5	350	3.05	87
69	12 2		312	528	78	5	5	352	3.05	72
70	12 3		312	450	78	5	5	441	3.05	89
71	12 4		312	502	78	5	5	435	3.05	71
72	10 5 a	Redwood R, 1998[20]	353	381	67	4	5	67	1.22	38
73	10 5 b		353	381	67	4	5	67	1.22	31
74	10 6		353	381	67	4	5	67	1.83	43
75	10 7		353	381	67	4	5	67	2.44	51
76	1	Zirakian T And Showkati H, 2006 [30]	234	176	64	4	6	180	3.60	20
77	2		234	176	64	4	6	180	4.40	20
78	3		234	176	64	4	6	180	5.20	20
79	4		332	207	73	5	7	210	3.60	30

80	5		332	210	73	5	7	210	4.40	29
81	6		332	212	73	5	7	210	5.20	29
82	FWL 1	Wenting et al. (2018) [28]	333	500	250	10	14	492	3.43	654
83	FWL 2		452	500	250	10	14	492	3.43	660
84	FWL 3		389	500	250	10	14	492	3.43	641

2. Description of Predictive equation for Capacity of Castellated Beams

Seven equations identified for predicting the capacity of castellated beams by various codes and researchers. The predictive equations by AISC design Guide 31[1], AS4100:2020[4], BS449 Part 2, Gandomi et al. equation (2011) [8], Mohebkhah et al. equation (2005) [15], Kerdal et al. [12] Equation (1984) has been taken for evaluation. All equations are empirical and semi empirical in nature. The confusion also aroused due to different notations adopted for various parameters in castellated beams by the codes and researchers. Hence, the following notations demonstrated Fig. 2 is adopted in this study.

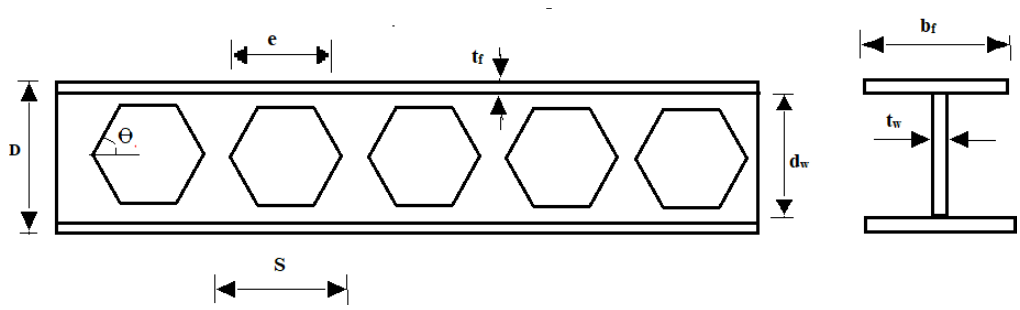


Fig. 2 Notations of parameters in Castellated Beams

AISC Design Guide[1]

American Institute of Steel Construction (AISC) – 31, Steel Design Guide[1] recommends extensive design methodology of Castellated and Cellular Beams. Chapter 3 explains the design procedure of beams. The moment carrying capacity of beams has been given in Cl. 3.4.1.2 from Equation 3.26 – 3.28 in code and same shown in 1a – 1c.

$e/t_w = 10, \qquad M/M_p = 0.587(0.917)^{\frac{2D}{e}} \leq 0.493$ (1a)

$e/t_w = 20, \qquad M/M_p = 1.96(0.699)^{\frac{2D}{e}}$ (1b)

$e/t_w = 30, \qquad M/M_p = 2.55(0.574)^{\frac{2D}{e}}$ (1c)

Where, $M_p = 0.25 t_w (e + 2b)^2 f_y$ (1d)

Interpolate between the equations based on e/t_w.

3.2 AS4100:2020[4]

Australian Standard (AS4100:2020)[4] provides some recommendations for steel open sections in Cl. 5.6.1.1. As Per this Code, the equation provided is not valid for member thickness less than 3 mm and design yield strength exceeding 690MPa.

$$M = \alpha_m \alpha_s M_s \leq M_s \quad (2)$$

Where,

α_m = Moment Modification Factor,

α_s = Slenderness Reduction Factor $= 0.6\left[\sqrt{\left[\left(\frac{M_s}{M_o}\right)^2 + 3\right]} - \left(\frac{M_s}{M_o}\right)\right]$

$M_o = \sqrt{\left[\left(\frac{\pi^2 EI_y}{l_e^2}\right) * GJ + \left(\frac{\pi^2 EI_w}{l_e^2}\right)\right]}$; $M_s = f_y Z_e$; $E = 2\times10^5$ MPa; $G = 8\times10^4$ MPa,

J = Torsional Constant = $\Sigma\left(\frac{bt^3}{3}\right)$; I_w = Warping Constant = $\frac{I_y t_f^2}{4}$.

3.3 BS 449-2[6]

British Standard 449 Part 2 provides Specification for the use of structural steel in building. BS[6] recommends the section capacity from simple bending equation as product of plastic section modulus and yield stress. The plastic section modulus is calculated at the hole.

$$M = Z_p f_y; \quad Z_p = \text{Plastic section Modulus at hole.} \quad (3)$$

Gandomi et al. equation (2011)[8]

New prediction model for load carrying capacity of castellated steel beams has been developed by Gandomi et al. [8] The authors developed two models for finding load capacity. The first model is based on Gene expression Programming (GEP) and second model based on least square Regression (LSR).

$$P_{GEP}\,(kN) = t_w\left(L\left(\frac{f_y - B}{S}\right) - 1\right) + (t_w - 4)(t_w - LC)^3\sqrt{(h_c + f_y)(f_y - t_w - 216)} - (t_f - LC)^2 + \left(\sqrt[3]{t_f + D} - 10\right)\left(t_w^2 - \frac{S}{6}\right) \quad (4)$$

$$P_{LSR}\,(kN) = 19.56LC + 3.926f_y + 0.937D - 0.455B + 111.794t_w - 19.869t_f - 0.409S - 48.641L - 1772.193 \quad (5)$$

Mohebkhah et al. equation (2005)[15]

Amin Mohebkhah et al. [15] have developed a predicting model for castellated steel beams based on regression analysis from nonlinear finite element study. COSMOS software package has been used for the study.

$$M/M_p = 0.8(\sqrt{\lambda^4 + 3} - \lambda^2) \leq 1; \quad (6)$$

$$\lambda = \sqrt{\frac{M_p}{M_{ocr}}} \quad (6a)$$

$$M_p = f_y [bt_f(h - t_f) + 36t_w(h - 6t_f)(5h - 6t_f)] \quad (6b)$$

$$M_{ocr} = \frac{\pi}{L}\sqrt{EI_y GJ}\sqrt{(1 + W^2)}, \quad (6c)$$

$$W = \frac{\pi}{L}\sqrt{\frac{EC_w}{GJ}}, \quad (6d)$$

Kerdal et al. Equation[12] (1984)

Kerdal and Nethercot studied the failure modes of castellated beams. They proposed strength of castellated beams under four point loading using the past experimental data.

$$P = 0.274 t_w f_y \left(\frac{D_c}{2} - 1.5 t_f\right) \quad (7)$$

Parameters Influencing

In general, the capacity of castellated beams depends on depth of beam, breadth of flange, thickness of flange, thickness of web, Opening length, shape of opening, opening angle, yield stress of material, shear modulus, warping constant, elastic and plastic section modulus, span of the beam. Table 2 shows the summary of parameters incorporated in various predictive equations for finding capacity of castellated beams. As per AISC[1] predictive equation, flange thickness, span, elastic and shear modulus does not influence the capacity of castellated beams. AS4100 predictive equation does not consider opening size, span as influencing parameters. As per BS standard[6], opening size, length, elastic modulus and shear modulus are not influencing parameters. This difference in opinion regarding among codes and researchers drove us to perform this study.

Table 2 Summary of parameters adopted in various strength equations

Eq. No.	Capacity Equation	f_y	D	b_f	t_w	t_f	S	L	ϴ	E	G
1	AISC[1]	✓	✓	✓	✓	×	✓	×	✓	×	×
2	AS4100[4]	✓	✓	✓	✓	✓	×	×	×	✓	✓
3	BS[6]	✓	✓	✓	✓	✓	×	×	×	×	×
4	Gandomi (GEP) [8]	✓	✓	✓	✓	✓	✓	✓	×	×	×
5	Gandomi (LSR) [8]	✓	✓	✓	✓	✓	✓	✓	×	×	×
6	Mohebkhah et al. [15]	✓	✓	✓	✓	✓	✓	✓	×	✓	✓
7	Kerdal et al. [12]	✓	✓	×	✓	✓	×	×	×	×	×

3. Research Significance

Numerous research efforts and recommendations on castellated beams have been reported across the globe. Seven such empirical and semi-empirical predictive equations reported in the codes and literatures have been collected. The influence of parameters of castellated for its capacity differs among the codes and researchers. Such deviation in prediction needs to be addressed properly, to estimate the capacity judiciously. Hence there is a need for assessing the accuracy of such equations. The evaluating equations from various sources are assessed statistically using 84 experimental data points collected in the literature. The variation of prediction of strength using most of the existing equations is inferred through statistical analysis[3].

4. Statistical Assessment of the Strength

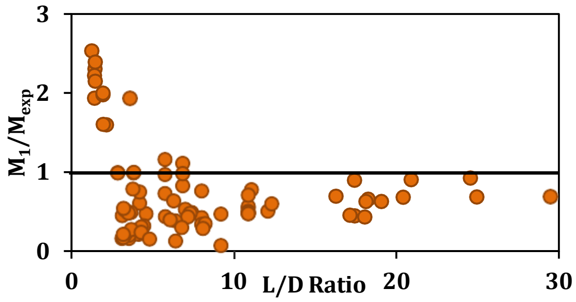
The empirical and semi-empirical equations proposed for predicting the capacity of castellated beams have been assessed for the accuracy of prediction using the selected 84 experimental test data for castellated beams. The experimental results from various sources are summarised in Table 1.

Table 3 Statistics of the ratio of Moment capacity of Predicted-to-Experimental

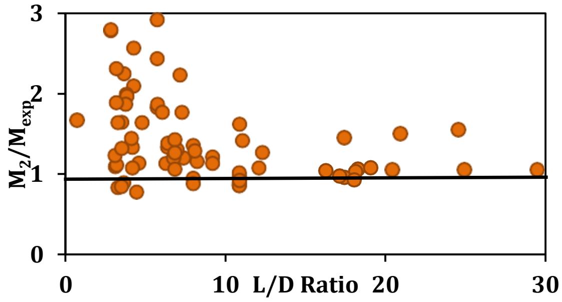
Ratio	Capacity Equation	Mean	Median	SD	CoV	R^2	% Predictor Error
M_1/M_{exp}	AISC[1]	0.8	0.5	0.8	1.0	0.6	-19.8
M_2/M_{exp}	AS4100[4]	1.9	1.3	1.5	0.8	0.5	110.0
M_3/M_{exp}	BS[6]	1.8	1.1	1.9	1.0	0.4	80.5
M_4/M_{exp}	Gandomi (GEP) [8]	2.1	1.6	1.9	0.9	0.6	119.0
M_5/M_{exp}	Gandomi (LSR) [8]	1.6	0.8	1.9	1.2	0.3	57.7
M_6/M_{exp}	Mohebkhah et al. [15]	0.8	0.5	0.9	1.1	0.2	34.8
M_7/M_{exp}	Kerdal et al. [12]	0.9	0.7	0.5	0.5	0.5	-14.2

The statistical assessment of the predicted moment capacity is an appropriate and easier way to describe the strengths and weaknesses of such predictive equations and enables in identifying the parameters to be retained and allows formulating another refined equation with improved accuracy in agreement with the experimental database. The moment ratio is defined as the ratio of the predicted moment capacity from the proposed equations-to-the experimental moment capacity. A statistical representation of the ratios of the moment capacity with 84 data points from castellated beam tests is shown in Table 3. If the mean, as shown in Table 3, is greater than 1.0, the prediction from such equations overestimates the strength and vice-versa.

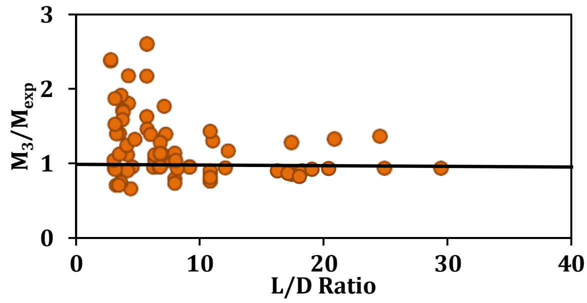
The median in Table 3 denotes the central scattering of all the data points predicted using the corresponding strength equation. The coefficient of variation (CoV) describes the dispersion of data points around the mean. Lower value of CoV indicates the lower dispersion of the data points around the mean. The coefficient of determination (R^2) quantifies the variance of the predicted equations from the experimental results. Higher R^2 value indicates the lower error between the strength using the predicted equations and the experimental results. The percentage predictor quantifies the error of individual data points with the predicted equation. If the percentage predictor error is positive, then it indicates the percentage overestimation by the corresponding equation and vice-versa. Graphic presentation is another way of analysing numerical data points. This is an effective method of understanding and interpretation of analysing the data points. The ratio of the predicted-to-measured moment vs. L/D ratio is shown as scatter diagram in Fig. 3.



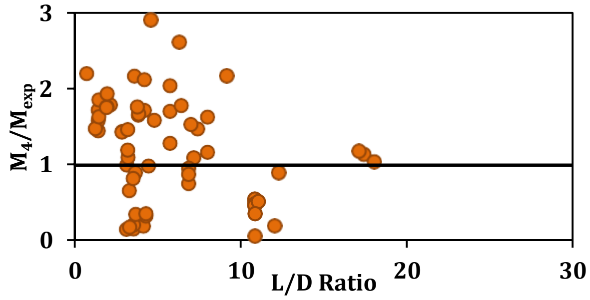
(a) AISC Equation[1]



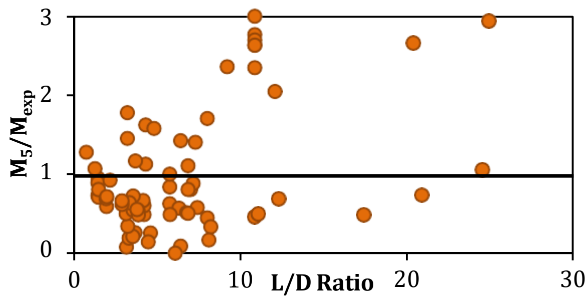
(b) AS4100 Equation[4]



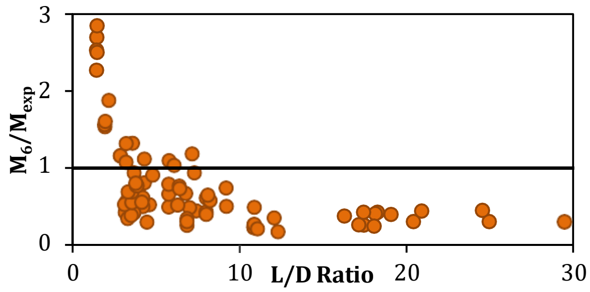
(c) BS Equation[6]



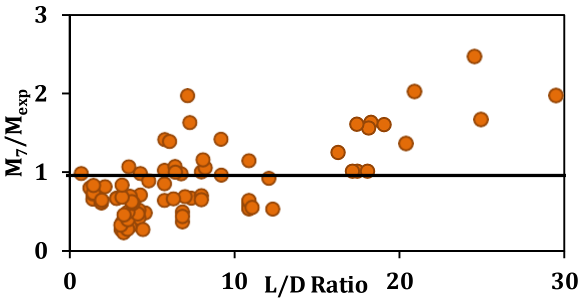
(d) Gandomi (GEP) Equation[8]



(e) Gandomi (LSR) Equation[8]



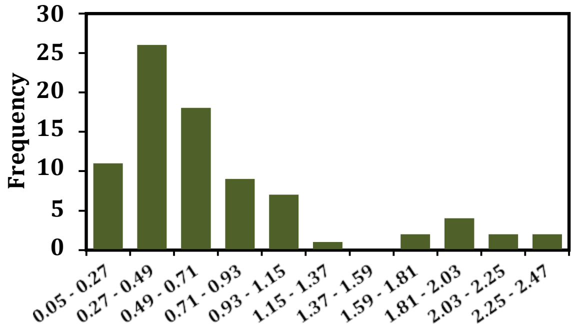
(f) Mohebkhah Equation[15]



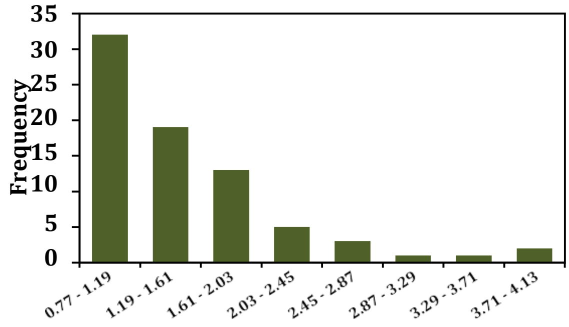
(f) Kerdal et al. Equation[12]

Fig. 3 Scatter of M/M_{exp} vs. Aspect Ratio

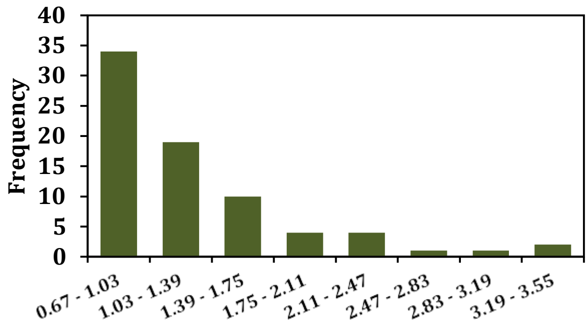
The frequency distribution diagrams, shown in Figs. 4, display the observations within an interval of the ratio of predicted-to-measured strength. This is a typical representation showing the distribution of different ranges among all the observations in a quantitative dataset. It is advantageous for describing the shape, centre and spread for better understanding of the distribution of the dataset. In the present study, Freedman–Diaconis rule is used for selecting the interval size of the frequency.



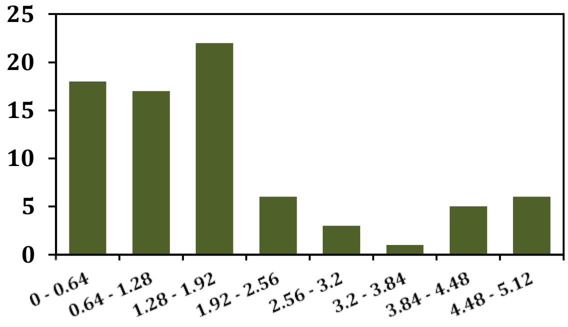
(a) AISC Equation[1]



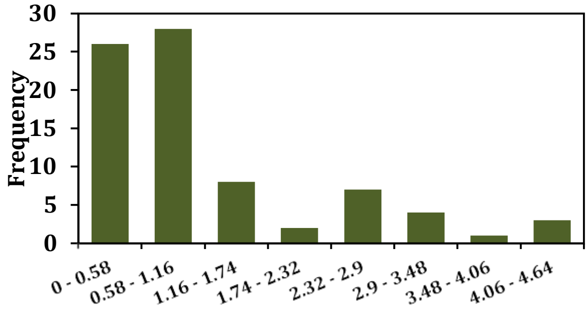
(b) AS4100 Equation[4]



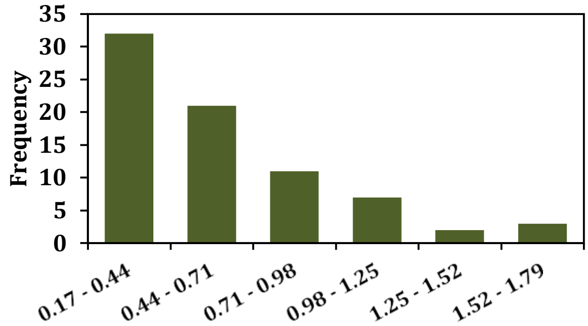
(c) BS Equation[6]



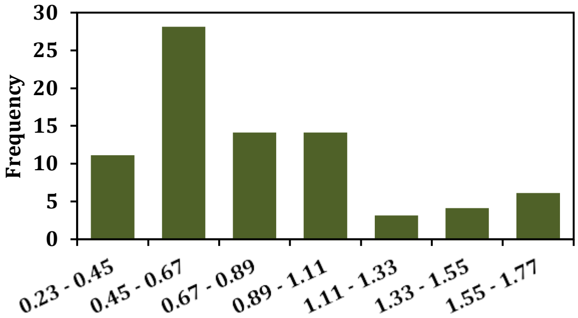
(d) Gandomi (GEP) Equation[8]



(e) Gandomi (LSR) Equation[8]



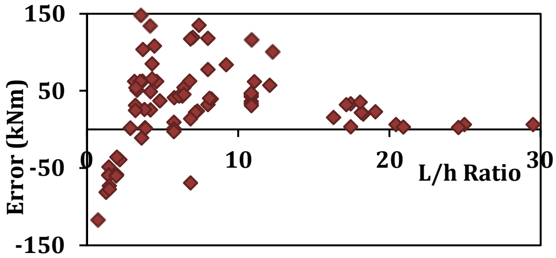
(f) Mohebkhah Equation[15]



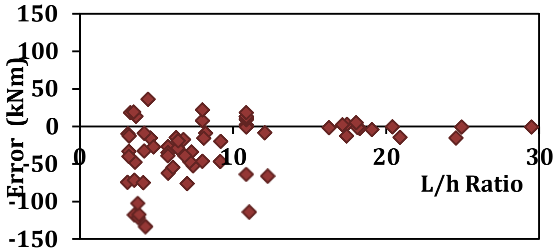
(f) Kerdal et al. Equation[12]

Fig. 4 Frequency Distribution of M/M_{exp} vs. L/D Ratio

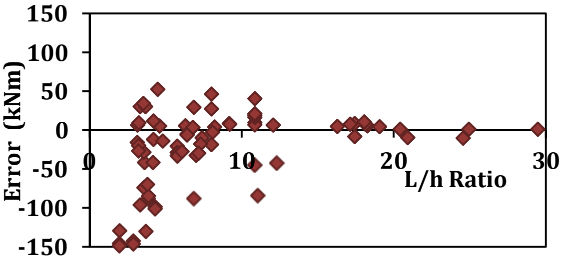
The error plot is graph that shows the residuals on the vertical axis and the independent variable on the horizontal axis. The difference between the observed value from the experiments and the predicted value from the equations is called the error or residual and plotted as shown in Fig. 5. The points below the horizontal axis shows that predicted values are higher than the experimental results which are unsatisfactory. In this aspect, the error plots are plotted and analysed.



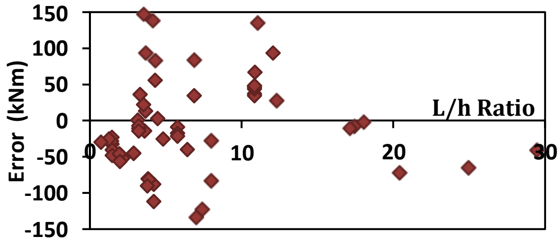
(a) AISC Equation[1]



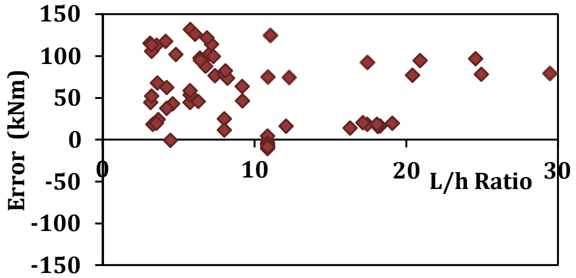
(b) AS4100 Equation[4]



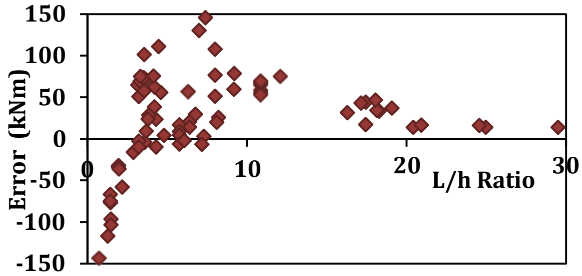
(c) BS Equation[6]



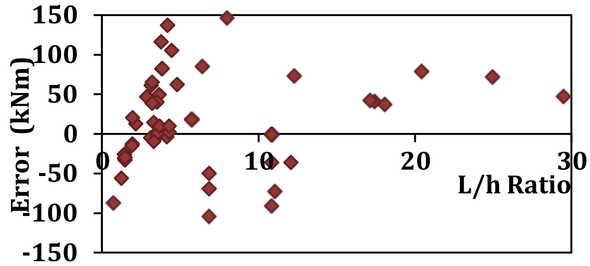
(d) Gandomi (GEP) Equation[8]



(e) Gandomi (LSR) Equation[8]



(f) Mohebkhah Equation[15]



(f) Kerdal et al. Equation[12]

Fig. 5 Error Plots

A box and whisker plot is a graphical representation that informs the five-number summary, i.e. lower extreme, lower quartile, median, upper quartile, and upper extreme. This box and whisker plots indicate whether a distribution is skewed or not, and whether there are potential unusual observations in the data points or not as shown in Fig. 6.

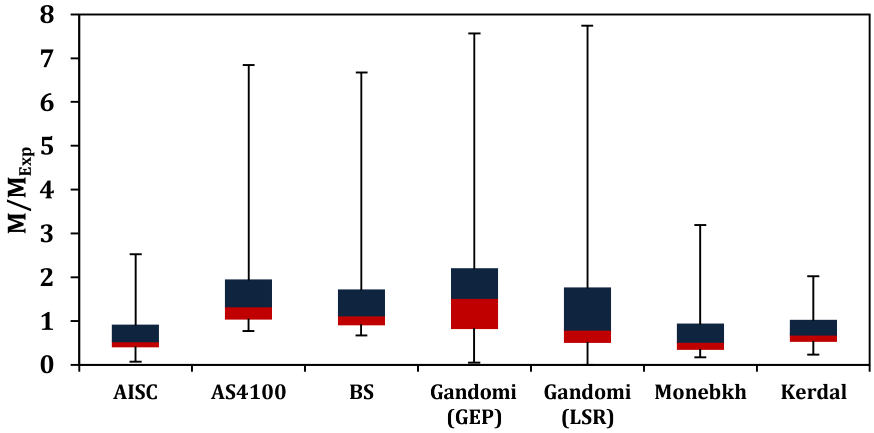


Fig. 6 Box and Whisker Plots for distribution of ratio of predicted measured strength

5. New Predicted Model

Regression analysis has been carried out using NCSS 2023 software. "NCSS" stands for "Number Cruncher Statistical System". NCSS is a comprehensive and powerful statistical software package used for data analysis and statistical research. It provides a wide range of statistical tools and procedures to analyse data, conduct hypothesis tests, create graphs, and generate reports. It offers a graphical interface that allows users to easily input data, select the desired statistical methods, and interpret results without the need for programming. As Kerdal et al. [12] equation performs better in our analysis, the same skeleton has been considered for developing new model. The new prediction equation has been developed as follows.

$$M = f_y \times Z;$$

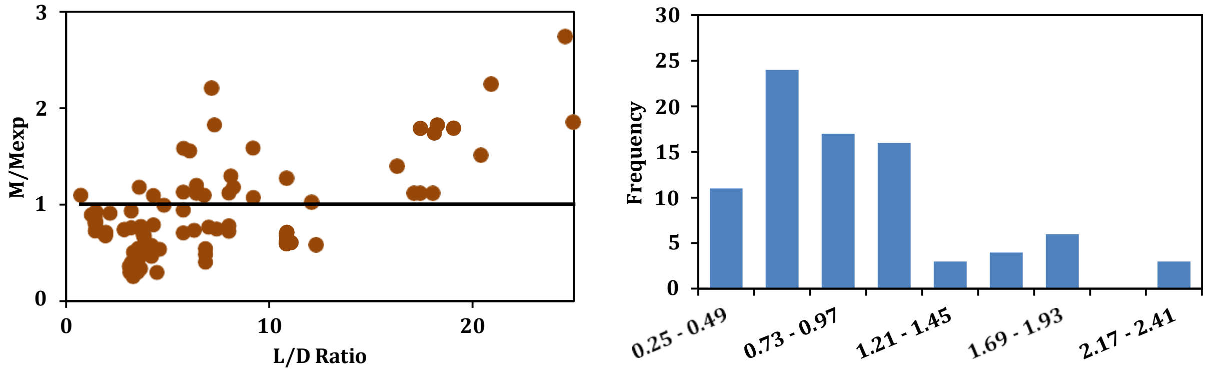
$$\text{Where, } Z = 0.154 t_w L \left(\frac{D}{3} - 1.1 t_f\right)$$

The proposed model is semi empirical in nature. The proposed model performs well in mean as 0.9. The proposed model has less standard deviation than other available predictive equations. The coefficient of determination has been improved and is about 0.83. The percentage error is very low as 4.3%. this is shown in Table 4.

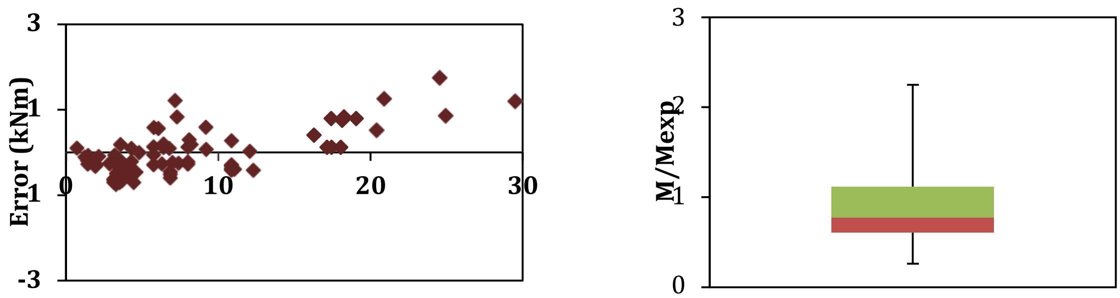
Table 4 Statistics of the Moment capacity Ratio of Predicted-to-Experimental of New Model

Ratio	**Mean**	**Median**	**SD**	**CoV**	**R^2**	**% Predictor Error**
M/M_{exp}	0.9	0.77	0.43	0.47	0.83	-4.3

The graphical means of statistical analysis is shown in Fig. 7. It can be seen that the equation performs better than others and is reflected in these statistical analysis. Error plot shows that how close the new prediction equation with experimental results. It can be also observed that the whiskers are less in length and box is close to 1. This shows the skweness is low.



(a) Scatter Plot **(b) Frequency Distribution**



(c) Error Plot **(d) Box and Whisker Plot**

Fig. 7 Graphical Representation of Statistical Analysis

6. Results and Discussion

The statistical assessment of the accuracy of prediction of strength of castellated beams has been verified statistically. The better performances of predictive equation in case of mean are Kerdal et al. equation[12], AISC equation[1] and Mohebkhah et al. equation[15] are 0.9, 0.8 and 0.8 respectively. British Standard, Gandomi et al.(LSR) [8] and Kerdal et al. equations[12] performs better for median with 1.1, 0.8 and 0.7 respectively. Standard deviation and coefficient of variation is low for Kerdal et al. equation[12]. Coefficient of determination is better in case of AISC[1] and Gandomi et al. (GEP) equation[8]. Prediction error is low in case of Kerdal et al. equation[12] followed by AISC equation[1].

Some graphical statistical tools are also performed to study the predictive equation performance. The scatter plot is seen in Fig. 2. The points above 1.0 of the horizontal axis indicate that the predicted the strength using the equations is greater than the experimental results, which are not satisfactory. In this aspect, Kerdal et al. equation[12] and BS equation[6] seems better than others. In the present study, Freedman–Diaconis rule is used and frequenct distribution is plotted. As per frequency distribution plot seen in Fig. 3, AS equation[4] and BS standard[6] shows satisfactory results. Close call for error is seen from error plot in Fig. 4 and AS equation[4], BS equation[6] and Kerdal et al. equation[12] seems better in this aspect. A box and whisker plot, as shown in Fig. 5, is useful to indicate the skewness of the scatter data distribution. AISC[1] and Kerdal et al. equation[12] shows admirable results in this feature with less whisker lengths. The equations with best performance are shown in Table 5.

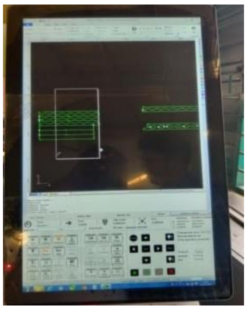
Table 5 Equations with the Best performance

Statistical Parameter	Equation with Best performance
Mean	Kerdal et al. equation[12], AISC equation[1] and Mohebkhah et al. equation[15]
Median	British Standard, Gandomi et al. (LSR)[8] and Kerdal et al. equations
Standard Deviation	Kerdal et al. equation[12]
Coefficient of variation	Kerdal et al. equation[12]
Coefficient of Determination	AISC[1] and Gandomi (GEP) equation[8]
Predictor Error	Kerdal et al. equation[12] and AISC equation[1]
Scatter Plot	Kerdal et al. equation [12] and BS equation[6]
Frequency Distribution	AS equation[4] and BS Equation[6]
Box and Whisker Plot	AISC[1] and Kerdal et al. equation[12]

7. Validation with Experiment

The process of manufacture of castellated beams involves material selection, design of beams, CNC Cutting, alignment, welding, Grinding. 4 mm steel plates have been chosen for construction of castellated beams[2]. The castellation pattern is typically created using Computer Numerical Control (CNC) cutting. After the openings are cut, the plate is flattened to ensure all the castellation are aligned properly. Welding is done for connections at the cut edges of the castellated beam. The flanges are also welded fully with this castellated web portion. The beam manufacturing process is shown in Fig. 8.

(a) Steel Plate



(b) Drawing Feed in CNC

(c) Plate placement in CNC

(d) CNC Laser Cutting (e) Welding (f) Finishing

Fig. 8 Preparation of Castellated beam

The testing of beams is done using 50 ton capacity reaction frame in Sona College of Technology in Salem, Tamilnadu, India. Beam is made simply supported and two point loading is given to study the flexural behaviour. The shear span is fixed about 430 mm and span of beam fixed about 1800 mm 25 ton capacity hydraulic jack is fixed and tightened sufficiently to avoid any movement of the jack. Two points loading is given with the help of a spreader steel beam under the jack. This is shown in Fig. 9. The loading has been applied with the rate of 0.2 kN/s. The reading has been taken until the load drops after reaching the peak load. Lateral torsional buckling failure has been observed.

(a) Loading Arrangement (b) LTB Failure

Fig. 9 Loading Arrangement and Failure

The strength obtained from testing is 38 kN and corresponding moment is 16.34 kNm. This has been correlated with all the predictive equation. The ratio of moment predicted to acquired is calculated and listed in Table 6. As per this table, Kerdal et al. equation[12], AISC equation[1] and Mohebkhah et al. equation[15] gives the results as 1.19, 1.24 and 0.85 respectively. This reinforces the statistical evaluation results.

Table 6 Ratio of Moment Predicted to Obtained

	AISC [1]	**AS4100** [4]	**BS**[6]	**Gandomi (GEP)** [8]	**Gandomi (LSR)** [8]	**Mohebkhah et al.** [15]	**Kerdal et al.** [12]	**New Predicted Model**
M/M_{exp}	1.24	1.84	2.2	3.27	3.14	0.85	1.19	1.16

8. Conclusion

The statistical assessment of the prediction of capacity of castellated beams by various equations has been discussed. The predicted strength has been validated with the experimental results.

All these predicting equations show entirely different scatter due to their form and level of influence of parameters selected.

1. The strength predictions by Kerdal et al. equation[12] followed by AISC equation[1] are closely agreeable with the experimental results.
2. These equations still can be modified and improved for more betterment results agreeing with experimental.
3. Improved new model has been proposed which performs well in comparison with others.

NOTATIONS

b_f	Breadth of Flange	mm
C_x	Warping Section Constant	mm^4
D	Total Depth of section	mm
d_w	Depth of web	mm
E	Modulus of Elasticity	MPa
E	Opening length	mm
f_y	Yield Stress of Steel	MPa
G	Shear modulus	MPa
I_w	Warping Constant	mm^4
I_x	Second Moment of Area about CG XX axis	mm^4
I_y	Second Moment of Area about CG YY axis	mm^4
J	Torsional Constant	mm^4
L	Span of the beam	mm^4
LC	Load condition variable	-
M_1	Moment Capacity as per AISC Equation[1]	kN-m
M_2	Moment Capacity as per AS4100:2020 Equation[4]	kN-m
M_3	Moment Capacity as per BS 449-2 Equation[6]	kN-m
M_4	Moment Capacity as per Gandomi et al. equation GEP Equation[8]	kN-m
M_5	Moment Capacity as per Gandomi et al. equation LSR Equation[8]	kN-m
M_6	Moment Capacity as per Mohebkhah et al. Equation[15]	kN-m
M_7	Moment Capacity as per Kerdal et al. Equation[12]	kN-m
S	Width of Web Post	Mm

t_f	Thickness of Flange	mm
t_w	Thickness of web	mm
Z_e	Elastic Section Modulus	mm^3
Z_p	Plastic Section modulus	mm^3
Ɵ	Angle of Opening	Degrees
α_m	Moment Modification Factor	-
α_s	Slenderness Reduction Factor	-
λ	Modified flexural torsional slenderness of castellated beam	-

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