# Finite Element Investigation On The Notch Sensitivity Of Castellated Beams

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## Abstract :

Castellated beams are powerful alternative to structures in civil engineering applications with their material saving, lightweight characteristics and cheapness. Castellated beams with hexagonal openings were examined for bending using Finite Element Analysis (FEA) with various parameters. During the analysis, beam was fixed at one end then load was applied in several ways as on the tip of the beam, on the midpoint and also uniformly distributed load was applied. Young's modulus was altered to represent different kind of materials for beam structure as 135000, 163750, 192500, 221250, 250000 MPa. Stress and strain results were evaluated under various loads. After comparing finite element analysis results with emprical results, it was noticed that finite element analysis found to be a practical and reliable method for bending analysis of castellated beams.

**Key words:** Castellated beams, hexagonal opening, bending analysis, FEA, notch sensitivity

## 1. Introduction

Castellated beams have many advantages like greater rigidity, larger section modulus, optimum weight–depth ratio, cheapness, serviceability through the web openings and aesthetic appearance [1]. Castellation is performed by cutting the beam in a zigzag pattern. One of the separated part is side shifted and welded to the other part. This process increases the height of the original beam (h) by the depth of the cut as shown in Fig. 1. Castellated beams are generally made from I sections by this process [2].

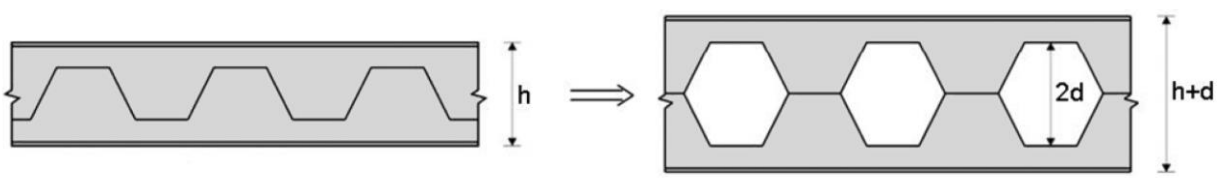



**Figure 1.** Castellation process of beam with Hexagonal openings [2]

In civil engineering, beams with openings are widely used to pass the under floor services ducts. Castellated beams are generally manufactured with circular or hexagonal openings, distributed through the beams with constant intervals. Castellation process leads into an increase in bending capability and reduction in the weight of the beam [3].

Several researches in literature are investigated on castellated steel beams under buckling, compression, tension, bending loads and different types of openings like circular, hexagonal, octagonal, rectangular, etc. as well as various types of materials were used. Yuan et al. [4] presented a new analytical solution for calculating the critical buckling load of simply supported castellated columns. They were pointed that the inclusion of web shear deformations significantly reduces the buckling resistance of castellated columns.

Wang et al. used FEA method to investigate deflection behaviors of the castellated beams in a fire [5]. The axial stiffness of a castellated beam is found to be smaller than the original solid web steel beam, the compression force due to the restrained thermal elongation in a castellated beam in a fire is lower than that in the solid web beam. In other research by same authors, the shear buckling behavior of the web-post in a castellated steel beam with fillet corner hexagonal web openings is investigated using the FEA method [6]. They were reported that the web post in a castellated steel beam with the proposed opening shape can achieve as good structural performance as that with circular openings.

Baylor et al. performed structural analysis of innovative composite timber I-joists with castellated webs [7]. The flanges of the joists were made of Norway Spruce and the webs were made of oriented strand board (OSB). The materials modeled as linear elastic orthotropic materials and the joists were analyzed using FEA method under tension and compression loads. It was reported that good correlation was found between the experimental results and the FEA simulations. The validated FEA models were compared to equivalent solid webbed joists and a geometric parametric study was carried out to determine the optimum web opening.

Mohebkhaha et al. developed a 3D FEA model and used it to investigate the effect of elastic lateral bracing stiffness on the inelastic flexural–torsional buckling of simply supported castellated beams with an elastic lateral restraint under pure bending [8]. It was found that for inelastic castellated beams, the effect of bracing is increased to some value as the lateral unbraced length increases and then decreased until the beam behaves as elastic. The effect of bracing depends not only on the stiffness of the restraint but also on the modified slenderness of the beam.

Gholizadeh et al. studied load carrying capacity of simply supported castellated steel beams under buckling load using nonlinear FEA [9]. To estimate the critical load, they were proposed an empirical equation. Also they employed back-propagation neural network and adaptive neuro-fuzzy inference system (ANFIS) and compared all these methods with each other. It was reported that better accuracy than the proposed equations is achieved by ANFIS and the neural network models.

Ozkan et al. modeled the notch sensitivity factor for shafts under bending stress using Artificial Neural Networks (ANN) and verified the accuracy of the model using Statistica software [10]. The model was developed using Pythia software so the accurate results could be obtained after input of shaft dimensions and the applied force without using notch sensitivity factor tables and any calculations.

Mercan et. al investigated concrete spandrel beams under combined loading as shear, torsion and bending [11]. They noticed that using a nonlinear 3D finite element model has difficulties thus they used numerical data obtained by ABAQUS/Standard software and compared the results with experimental data. By this way, beam response to various parameters were explored.

McEvily et al. pointed to empirical rules and determination of the fatigue notch factor and the stress concentration factor. They proposed an alternative approach to fatigue crack closure [12].

Yazdanmehr et al. developed caustics theory to determine stress intensity factors and used rounded V and U type notches under bending load [13]. They determined the stress intensity factor by measuring specific lengths in images. After comparing the results with FEM, they reported the reliability of the method.

Hmidan et al. used wide-flange steel beams those strengthened with carbon fiber reinforced polymer (CFRP) to determine the correction factor of stress intensity at the crack tip under bending load [14]. They developed 3D finite element models and an adaptive mesh formulation to predict stress singularity at the crack tip. After validating the model with the experimental data they were performed a parametric study.

This paper is focused on the notch sensitivity of castellated beams under bending stress. The interest of study is the notch sensitivity factor which affects the load carrying capability of the stressed beams.

## 2. Materials and Method

Empirical and FEA models of castellated beam with hexagonal openings are created. Castellated beams used in the analysis were modeled using Solidworks software. After importing the model to ANSYS software a parametric setup was conducted. Using same imported geometries bending analysis was performed under pre-determined type of loading and mesh is re-generated until results are collaborated with the empirical data thus the notch sensitivity was investigated.

### *2.1. Material properties*

Five different types of materials are used to model castellated beam with hexagonal openings. Material properties and experimental parameters are given in Table 1. Young's modulus were choosen between 135000 and 250000 GPa.

**Table 1.** Parameters used in analytical calculations and FEA

| Material | Profile type | Number of openings | Young's modulus (Mpa) | Load (N) | Load applying method |
|---|---|---|---|---|---|
| 1<br>2<br>3<br>4<br>5 | HE 260 B<br>with hexagonal<br>openings | 1<br>3<br>5<br>7 | 135000<br>163750<br>192500<br>221250<br>250000 | 2500<br>5000<br>10000<br>20000<br>30000 | Side<br>Center<br>Uniformly distributed |

### *2.2. Theory/calculation*

Axial force is applied to a cantilever beam, as shown in Figure 2. The length of the cantilever beam is $L$ and the applied axial force is $F$.

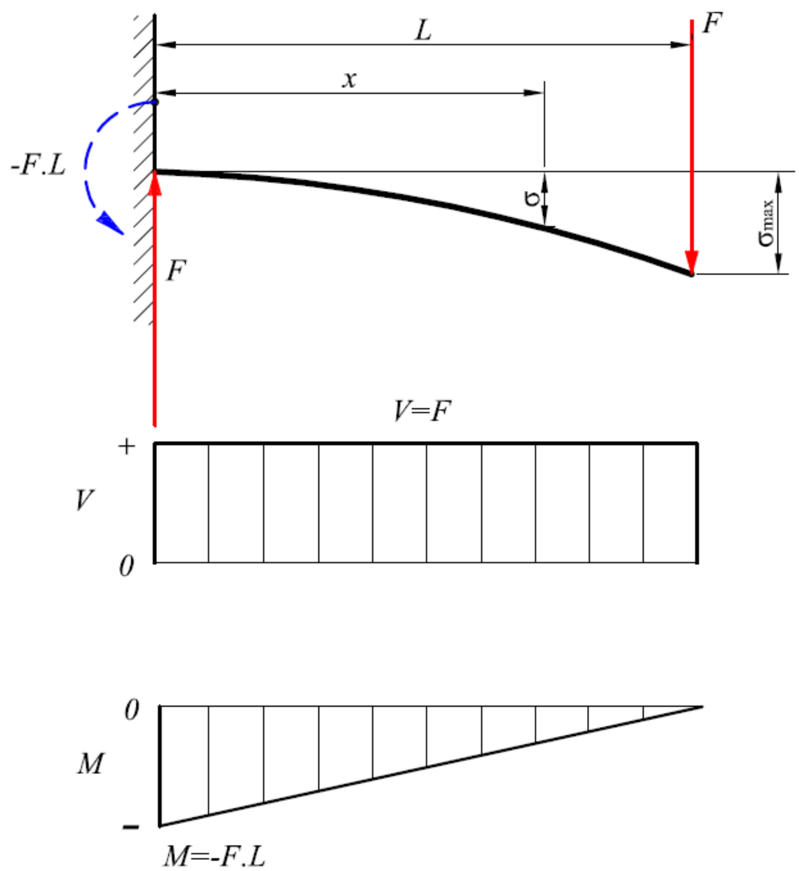



**Figure 2.** Model of cantilever beam and direction of forces

Eqs (1-4) are used for derivation of deflection (δ). Eq (5) is used to calculate maximum deflection $\delta_{\max}$ where $M$ is bending moment, $E$ is Young's modulus and $I$ is moment of inertia:

$$M_{AB} = (F.X) - M \quad (1)$$

$$y^{-} = \delta = \frac{1}{EI}\int[(F.X) - M]dx \quad (2)$$

$$\delta = \frac{1}{EI}[\frac{FX^2}{2} - M.X + C_1] \quad (3)$$

$$y^{=} = \delta_{max} = \frac{1}{EI}[\frac{FX^3}{6} - \frac{MX^2}{2} + C_1X + C_2] \quad (4)$$

Where $C_1 , C_2 = 0$ $and$ $X = L$ we obtain Eq (5)

$$\delta_{max} = \frac{1}{EI}[\frac{FL^3}{6} - \frac{ML^2}{2}] \quad (5)$$

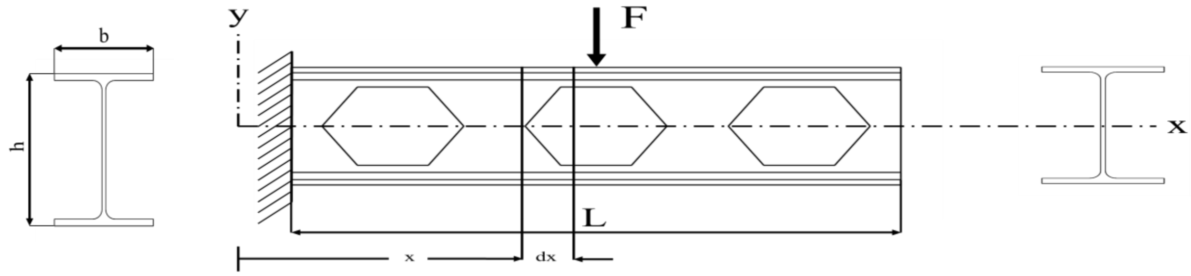



**Figure 3.** Schematic representation of analytic calculation method

$$\sigma_e = \int_{y1}^{c} \frac{(dM)y}{I} dA \tag{6}$$

$$\sigma_e = \frac{M_e c}{I} \quad (N/mm^2) \tag{7}$$

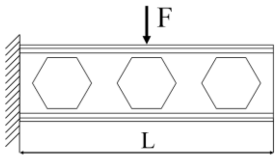
$$M_e = F.L/2 \tag{8}$$

Where c is the distance from the neutral axis to the outer surface (*h/2*) and moments of intertia of area, *I* is obtained using Solidworks as $I_{hexagonal}$=51356006.66 mm$^4$.

**Table 2.** Equations and typical analysis results for castellated beam with hexagonal openings under various loading types

| | Stress | Deformation |
|---|---|---|

***Mid- span loaded beam***



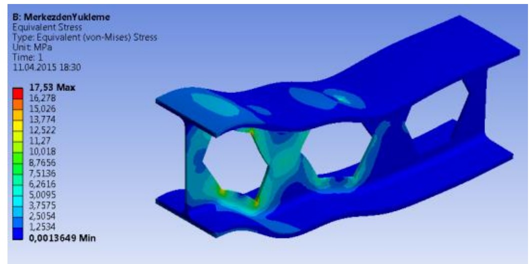

$$M_{BC} = R_A x - Fx + \frac{FL}{2} - M_R$$

$$y'_{BC} = \frac{1}{EI}[\left(R_A\frac{x^2}{2} - F\frac{x^2}{2}\right) + \frac{FLx}{2} - M_R x + c_1]$$

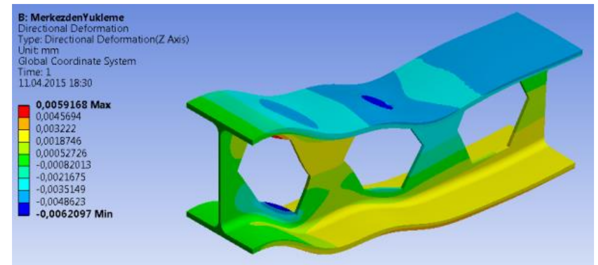
$$y_{BC} = \frac{1}{EI}[\left(R_A\frac{x^3}{6} - F\frac{x^3}{6}\right) + \frac{FLx^2}{4} - M_R\frac{x^2}{2} + c_1 x + c_2]$$

$$c_1 = F\frac{x^2}{2} + \frac{FL}{2}x$$

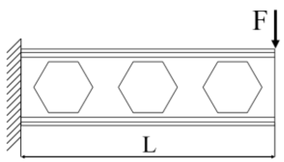
Stress:




Deformation:




***Tip loaded beam***

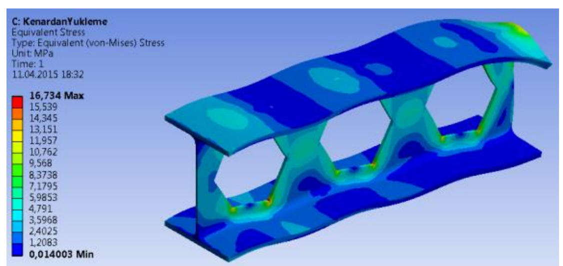



$$M_{AB} = R_A.x - M_R$$

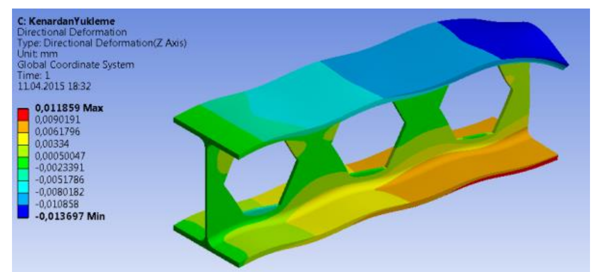
$$y'_{AB} = \frac{1}{EI}(R_A\frac{x^2}{2} - M_R x + c_1)$$

$$y_{AB} = \frac{1}{EI}(R_A\frac{x^3}{6} - \frac{M_R}{2}x^2 + c_1 x + c_2)$$

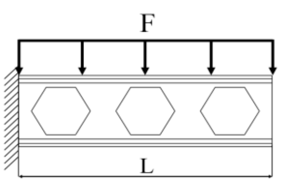
Stress:




Deformation:

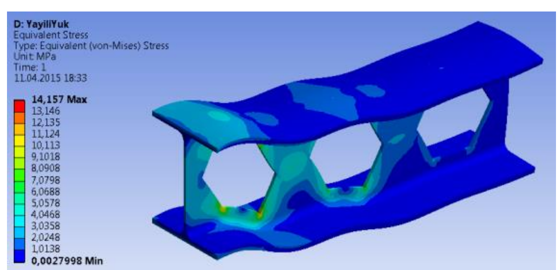



***Uniform loading on beam***

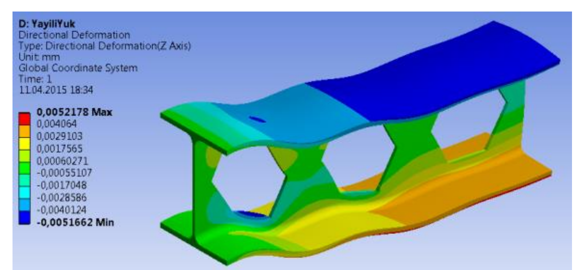



$$M_{AB} = -w\frac{x^2}{2} + R_A x - M_R$$

Stress:

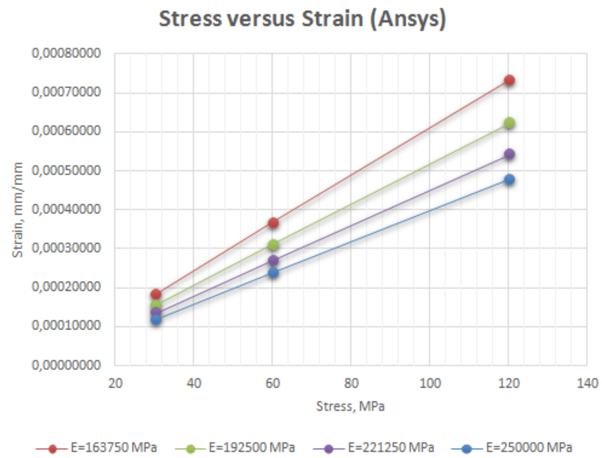



Deformation:

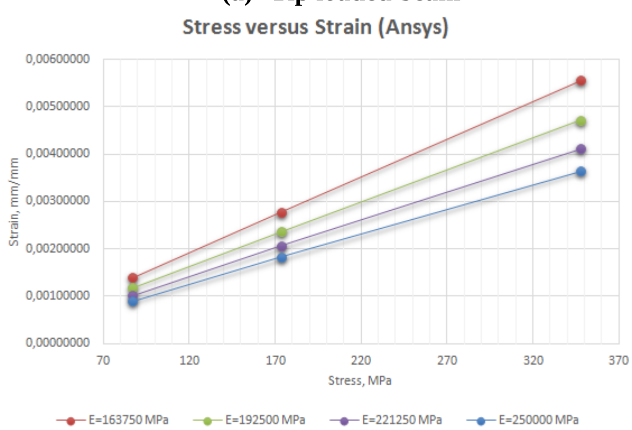


$$y'_{AB} = \frac{1}{EI}(-w\frac{x^3}{6} + R_A\frac{x^2}{2} - M_R x + c_1)$$
$$y_{AB} = \frac{1}{EI}(-w\frac{x^4}{24} + R_A\frac{x^3}{6} - M_R\frac{x^2}{2} + c_1 x + c_2$$

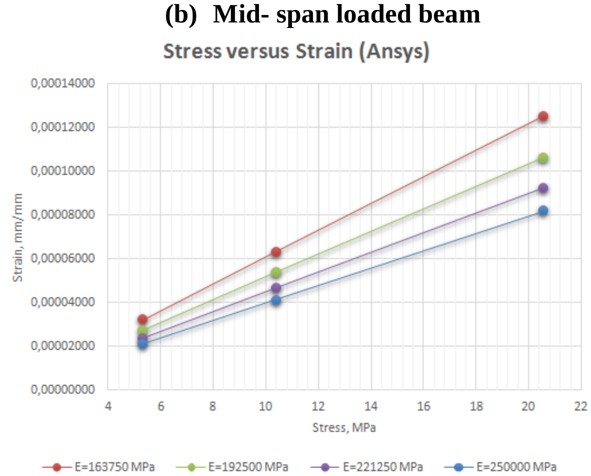
## 3. Results




**(a) Tip loaded beam**




**(b) Mid- span loaded beam**

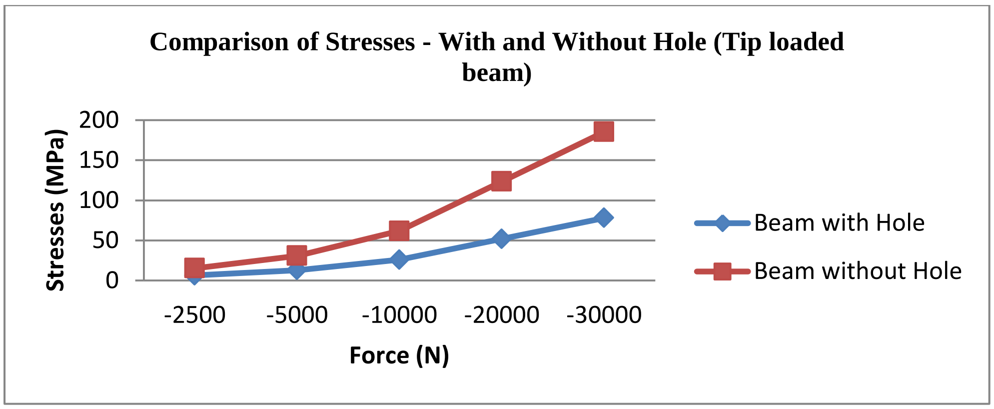



**(c) Uniform loading on beam**

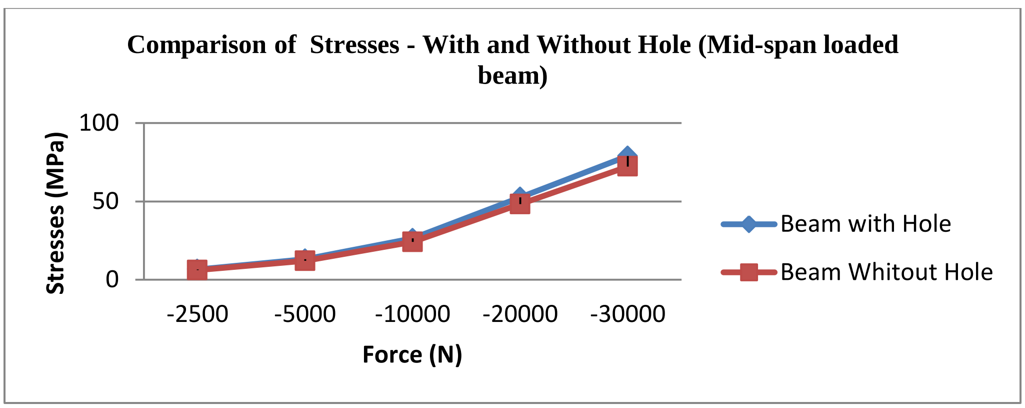
**Figure 4.** Stress versus Strain graphs (a) Tip loaded beam (b) Mid-span loaded beam (c) Uniform Loading on Beam

Figure 4 shows that Stress- Strain curve for different Young's modulus and 3 different loading states. Figure 5 shows that comparison of beam with and without openings Force- Stress states. 3 Different loding states were taken into account. Results were compared for defining the Notch Sensiticity factor.

(a)




(b)




(c)

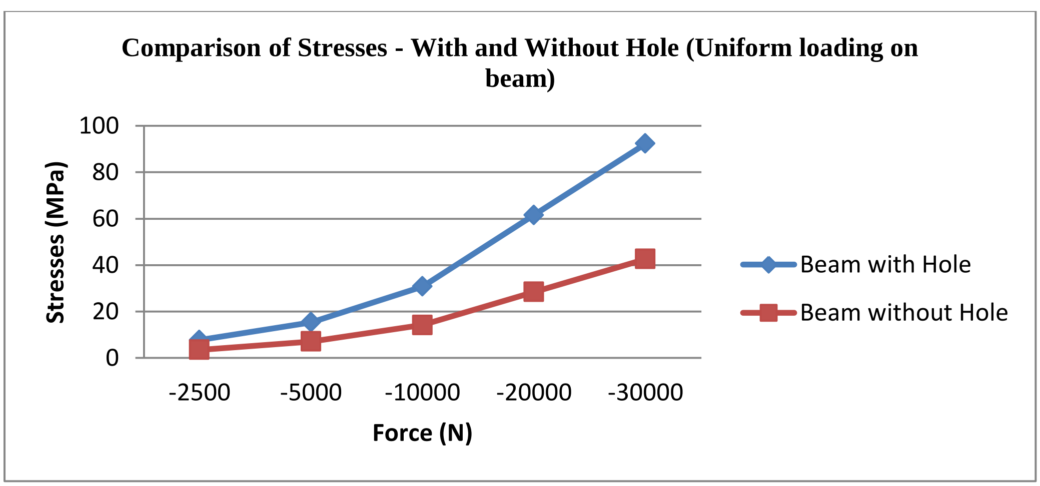


**Figure 5.** Comparison of Stresses on castellated beams with and without hole (a) Tip loaded beam (b) Mid-span loaded beam (c) Uniform loading on beam

In this study 3 different scenarios were taken into account. These were tip loaded beam, mid-span loaded beam and uniform loading on beam. Notch sensitivity factor was tried to be obtained for 2 different profile types. These profile types were with hole and without hole beam. FEA analysis were performed. While performing analysis using ANSYS, different material types were taken into account. Results were compared with each other.

$$\sigma_{max} = K.\sigma_{\mathrm{nom}} \tag{9}$$

Table 2. Defining the Notch Sensitivity Factor for different loading states.

| | Tip loaded beam | Mid-span loaded beam | Uniform loading on Beam |
|---|---|---|---|
| Notch Sensitivity (K) | 2.377119 | 1.091166 | 2.165385 |

## Conclusions

In this study, the Notch sensitivity factor of the bending stresses of the castellated beams with and without hole was revealed. Empirical model and FEA model solutions were compared with each other. Optimum FEA mesh model was determined according to empirical solution. Then FEA model was developed. In the FEA model, beams with hexagonal openings was modeled and analysed. Profile stresses of the castellated beams with and without hexagonal opening were compared. Then, Notch sensitivity factor was determined for 3 types of loading states.

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