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AURUM MÜHENDİSLİK SİSTEMLERİ VE MİMARLIK DERGİSİ
*AURUM JOURNAL OF ENGINEERING SYSTEMS AND ARCHITECTURE*

**Cilt 6, Sayı 2 | Kış 2022**
*Volume 6, No 2 | Winter 2022, 225-237*

**ARAŞTIRMA MAKALESİ / RESEARCH ARTICLE**

# DIMENSION ANALYSIS OF BENDING PERFORATED BEAMS WITH THE EVOLUTIONARY TOPOLOGICAL OPTIMIZATION METHOD

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**GELİŞ TARİHİ/RECEIVED DATE: 20.09.2022 KABUL TARİHİ/ACCEPTED DATE: 27.10.2022**

***Abstract***

The aim of this study is to determine the optimal shape and clearance of the web openings in order to both increase the carrying capacity and decrease the weight of classic perforated beams by using evolutionary topological optimization technique. The effects of the optimal shape and web openings has been obtained by the application of the evolutionary topological optimization through finite elements method, and then the obtained optimal beam has been compared with widely used perforated beams in the market by using stress and displacement analysis. The designed beam seemed to have more advantages than the widely used ones in industry with a less weight and higher carrying capacity. With the topology optimization, the usual classic perforated beams' geometry has been changed and stiffness was improved.

***Keywords:*** Optimization, Castellated Beam, Cellular Beam, Perforated Beam, Evolutionary Optimization, Topology Optimization, Structural Optimization

## EVRİMSEL TOPOLOJİK OPTİMİZASYON YÖNTEMİYLE DELİKLİ KİRİŞLERİN BÜKÜLMESİNİN BOYUT ANALİZİ

***Özet***

Bu çalışmanın amacı, klasik delikli kirişlerin hem taşıma kapasitesini artırmak hem de ağırlığını azaltmak için ağ açıklıklarının optimal şeklini ve açıklığını evrimsel topolojik optimizasyon tekniği kullanarak belirlemektir. Sonlu elemanlar yöntemi ile evrimsel topolojik optimizasyonun uygulanmasıyla optimal şekil ve ağ açıklıklarının etkileri elde edilmiş ve daha sonra elde edilen optimal kiriş, gerilme ve yer değiştirme analizi kullanılarak piyasada yaygın olarak kullanılan delikli kirişlerle karşılaştırılmıştır. Bu çalışmada tasarlanan kiriş, daha az ağırlık ve daha yüksek taşıma kapasitesi ile endüstride yaygın olarak kullanılanlardan daha fazla avantaja sahip görünüyordu. Topoloji optimizasyonu ile alışılmış klasik delikli kirişlerin geometrisi değiştirildi ve sertlik iyileştirilmiştir.

***Anahtar Kelimeler:*** Optimizasyon, Petek Kiriş, Boşluklu Kiriş, Evrimsel Optimazasyon, Topoloji Optimzasyon, Yapısal Optimizasyon.

## 1. INTRODUCTION

The great idea of increasing the height of the I-beam by making a hole has been used for about hundred years (Tsavdaridis vd, 2015). The aim of this is to increase the stiffness by increasing the moment of inertia (Srimari and Das, 1978). Research on beams has mainly focused on castellated beams which have hexagonal web openings and cellular beams circular web openings as a result of zigzag cut (Sharifi vd 2020). The use of cellular beams instead of castellated beams in constructions began in the early 90's. One of the biggest reasons for this change is aesthetic concerns (Weidlich vd 2021, Knowles 1991, Redwood 1968, Kerdal and Nethercot 1984, Hosain and Spiers 1970, Ward 1990). The most noticeable features of perforated beams are its high weight-bearing ratio and aesthetic appearance. In addition to the increased carrying capacity, the low weight means fewer loads on the construction being manufactured. One of the benefits of the web opened in addition to the aesthetic beauty it adds to the building is that it increases the useful floor height as building installations pass through these spaces.

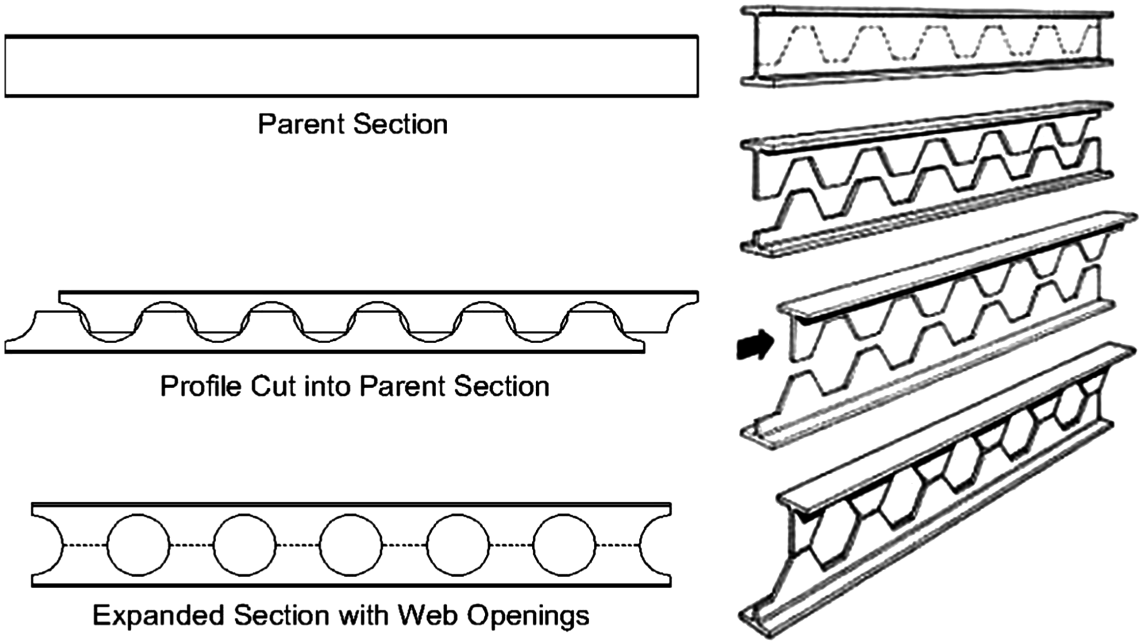



**Figure 1.** Perforated beam manufacturing process

Almost all the perforated beams are manufactured by cutting the standard I profile in a zigzag shape and then welding the two equal halves of the beam by sliding them a half step relative to each other. (Figure. 1) In order to save on cost, time and labor, this method is the most frequently used technique in the manufacturing area. However, manufacturing of complex shapes is difficult or impossible in this method.

## 2. BEAM OPTIMIZATION

In general, there are two kinds of optimization methods. These are deterministic optimization which cannot be based on any assumptions and probabilistic optimization which is based on probability (Lagaros vd, 2008). In this study, optimization of evolutionary bottom topology which is involved in probabilistic optimization has been used for solving the optimization problem. In addition, there are three types of design-based optimizations: sizing, shape and topological. (Figure 2)

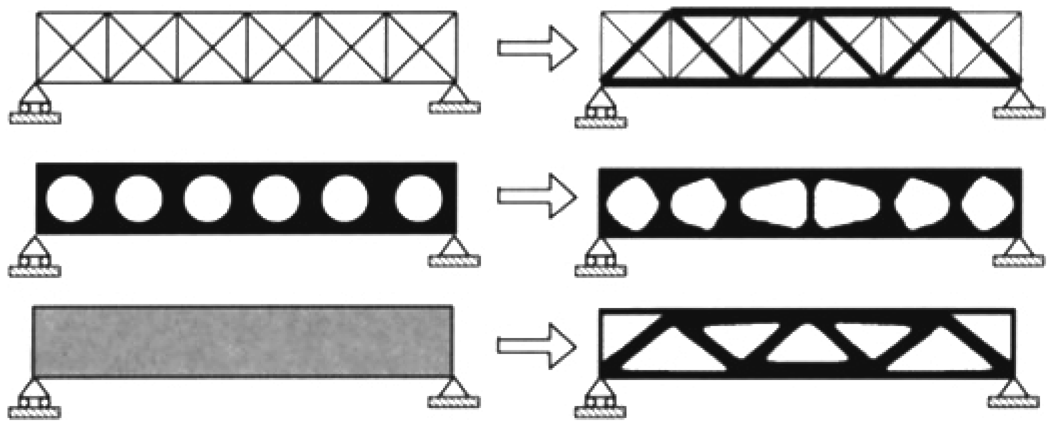



**Figure 2.** Structural optimization (a)sizing optimization (b)shape optimization, and (c)topology optimization (Tsavdaridis vd. 2015).



The design-based optimization aims to reduce manufacturing costs, especially in mass production in which a small decrease in the unit cost results in huge savings (Belegundu and Chandrupatla). The aim of sizing optimization is to decrease the weight into the lowest possible value under certain limit values. In shape optimization, on the other hand, it is aimed to increase the performance of the work piece by modifying its shape.

In topological optimization, the designer aims to design the most suitable work piece for manufacturing (Lagaros vd, 2006). Structural topological optimization is closely related with determining the web opened at the designable number and location to be used in this (Xie and Steven, 1993). Topology optimization approaches often require additional post-processing to generate a manufacturable topology with smooth boundaries (Rostami vd, 2021)

It is possible to find numerous studies in the open literature. However, studies on the topological optimization of the web opening and location are rather lacking. Therefore, this study fills this gap, by applying a new structure for the first time to the beams with a higher strength and lower displacement values than widely used beams which can be manufacturing by castellation.

One of these few studies is the evolutionary structure optimization that Lagaros at all conducted. The purpose of this work was to optimize the design of 3D steel structures with I-section beams. The optimization problem has been formulated as a combined sizing, shape and topology optimization problem. While the number and size of the web opened of the beams constitute the topology and shape design variables respectively, the cross-sectional dimensions of the columns and beams constitute the sizing design variables (Hosain and Spiers, 1970)

An alternative approach is the perforated beam optimization by using harmonic optimization, which was used in one of Erdal at all studies. The design problem of perforated beam is formulated as the optimum design problem. Harmony search and particle swarm optimization methods are used to solve the design problem. The design algorithms based on these two techniques select the optimum region of a cellular beam subjected to general loading to be used in producing the optimum web opened dimension and the optimum number of holes in the cellular crossover. This choice was made as design constraints were provided and the perforated beam was made to have the lowest weight (Erdal, Doğan and Saka, 2011)

Then Kingman proposed a beam web opened design based on the results of topology optimization on standard I profiles. The nonlinear finite element analysis technique is used to determine the load carrying performance of the optimized beam compared to conventional cellular beams. The optimized beam has been found to perform well in terms of load bearing capacities and stress intensity. The obstacles against the implementation of the topology optimization technique for the routine design of the beam web opened are emphasized. In detail, a parametric topology optimization study was performed to determine the optimal opening topology for large diameter beam sections which were found in practice. Thereafter, an optimal web opened configuration is proposed which was generalized on the results of the parametric study. With this optimal web opened configuration, a shape optimization study is expected to be needed to maximize the efficiency of the beams (Kingman vd, 2013)



In 2015, Travdaridis at all focused on the application of the structural topology optimization technique to design the perforated I profile as an intervention to replace traditional castellated beams containing the elliptical sparse and finite element model, and to better understand the related mechanisms when subjected to bending and shearing movements. Based on the results of parametric studies, optimal network latency configuration is recommended. A finite element analysis is used to determine the performance of the optimized beam compared to the traditional commonly used castellated beam. It has been found that the optimized beam exceeds load carrying capacities, deformations and tensile strengths. The obstacles against the application of the topology optimization technique for the routine design of the beam mesh have been emphasized (Tsavdaridis vd, 2015)

In 2017 Çiftçioğlu weight optimization of steel frames with cellular beams are carried out. Besides, the behavior of optimum structural system under external loads was investigated by use of finite element analysis (Çiftçioğlu, 2017)

In this study a new perforated beam was designed with optimum web opening geometry and dimensions, with a higher weight-bearing ratio, and easy to manufacture with a low cost. The stress and displacement analysis for the perforated beam were obtained as a result of this study will be conducted in the Ansys computer software by using through finite elements method, and then the results will be compared to the analysis results of widely used perforated beams in the market.

## 3. MATERIALS AND METHOD

### 3.1. Materials and Dimensions

An I sectioned of St 37 steel (200×100×3000 mm) was selected as a target material. I shaped profile has been used as the work piece in the whole work (ozcedemir, access date: 24,19.2021). Approximately 3 meter spans have been selected as the profile width. The reason for the approximation of the spans is that slight variations are observed in the beams of different types depending on the web opened and the shape. For example, while the spans of standard I-profile in this study is 3 meters, the spans of the cellular beam manufactured from IPE200 is 3.156 meters.

The optimization method used in this study is the finite elements method as Sigmund and Peterson have announced (Sigmund and Petersson). Commonly used solid isotropic material Penalization technique has been applied as well in order to facilitate the solution of the optimization problem (Rozvavy, 2009)

### 3.2. Modeling of Materials

All the work pieces in this study are modeled as 3d solid with 6 DOFs, because the computer analyze results for the work pieces modeled as 2d Shell with 3 DOFs might give inconsistent results with actual experiments as can be seen in the Vierendeel effect example (Kerdal and Nethercot, 1984) Also buckling phenomenon is one of the most important issues in steel members due to their slender systems. In general, I-shaped beams under load inside the plane, are prone to local and lateral torsional buckling, depending on the web slenderness, flange slenderness as well as overall slenderness of the beam (Hosseinpour and Sharifi, 2021)



Finite elements method based Ansys mechanical computer software has been used in modeling the IPE profile to which topological optimization will be applied. Creation of all the nodes and elements which form the mesh has not been left to the software and has been done manually. For the hoods, the elements constituting the mesh are 47.2 × 5 × 5mm. The meshing was manually done by using 5×5×5 mm elements in the body of IPE 200 profile. The reason for this being done manually is that in the evolutionary topological optimization applied, it is necessary to know each element's address.

In this case, 13 holes calculated by the following equation were modeled on the workpiece in order to apply evolutionary optimization. In other words, the border value is added.

$$\mathbf{e} = \left(\frac{\mathbf{L} - (\mathbf{n_{total}}.\,\mathbf{2}.\,\mathbf{b})}{\mathbf{2}.\,\mathbf{n_{total}}}\right) \tag{1}$$

Where (L) is castellated Steel I beam span, (b) and (e) are size of hole's parameter and (n_total) is the number of holes on work piece.

In the comparative analysis between the optimal perforated beam obtained and the other perforated beams used in the market, finite elements method based Ansys workbench has been used and meshing measuring was done by automatically entering 5mm limit.

### 3.3. Optimization Algorithm

The optimization algorithm used in this study is based on stress values (Eq. 2). The strength applied to IPE 200 profile is calculated as:

$$\boldsymbol{\sigma} = \frac{\mathbf{M}(\mathbf{h}/_{\mathbf{2}})}{\mathbf{I}} \tag{2}$$

Where, $I$ represents the moment of inertia, $h/_2$ represents the distance from center of mass to the head surface which where the stress reaches the highest value and $M$ represents the bending moment. Using this equation, force is applied on the work piece to allow the yield stress to be observed.

After calculating the maximum tensile and compressive stresses for each element by using the computer, it is required to take the absolute values of these stress measurements because it provides simplicity while making calculations with the limit values.

$$\boldsymbol{\sigma}_{*} \quad \left( \qquad\qquad \right] \quad \boldsymbol{\sigma_t < F_1 \Lambda \, \sigma_c < \; F_1} \tag{3}$$



If these three statements (Eq. 3) are satisfied, the element is deleted, and the loop starts again.

Thus, the optimization problem subjected to stress constraint is defined as:

$$\begin{aligned} &\textbf{Minimize}: \mathbf{C} = \mathbf{q}^{\mathbf{T}}\mathbf{K}\mathbf{q} \\ &\textbf{Subject to } \mathbf{Q}^{*} - \sum_{\mathbf{i}-\mathbf{1}}^{\mathbf{N}} \mathbf{Q}_{\mathbf{i}}\mathbf{x}_{\mathbf{i}} = \mathbf{0} \end{aligned} \tag{4}$$

Where is $C$ the mean compliance, $q$ is stress vectors, $K$ is the global stiffness matrix and $Q_i$ is the element stress, $Q^*$ is the endorsed total beam stress, and $N$ is the number of total elements. In additionally, $x_i$ indicates binary element variable that is equal to 0 in case of absence or 1 in case of presence of an element. The constraint functions are as shown below.

$$\mathbf{g_1} = \mathbf{M_u} - \mathbf{M_p} = \mathbf{0} \tag{5}$$

In order to ensure the safe bending capacity of the beam, the applied moment value (($M_u$)) under load should not exceed the plastic moment (($M_p$)) capacity as shown in the $g_1$ constraint function mentioned above.

The following $g_2$ constraint function defines that the shear force (($V_{smax}$)) generated on the supports should be less than the acceptable shear force (($P_s$)).

$$\mathbf{g_2 = V_{smax} - |P_s| < 0} \tag{6}$$

The $g_3$ constraint function states that the shear force (($V_{0max}$)) calculated at the web opening should be smaller than the allowable vertical shear force ($P_{vy}$).

$$\mathbf{g_3 = V_{0max} - P_{vy} \leq 0} \tag{7}$$

he $g_4$ constraint function states that the calculated horizontal shear force ($V_{hmax}$) should be smaller than the allowable horizontal shear force ($P_{yh}$).

$$\mathbf{g_4 = V_{hmax} - P_{yh} \leq 0} \tag{8}$$

The $g_5$ constraint function states that the maximum moment value ($M_w$) occurring in any section should be less than the safe body moment ($M_{max}$).

$$\mathbf{g_5 = M_w - M_{max} \leq 0} \tag{9}$$

The $g_6$ constraint function shows the relationship between the external force ($P_0$) and external moment ($M$) applied to the section body, and the plastic moment capacity ($M_p$) and force capacity ($P_u$).

$$\mathbf{g_6 = \frac{P_0}{P_u} + \frac{M}{M_p} - 1 \leq 0} \tag{10}$$

The $g_7$ constraint function shows the relationship between the applied axial load ($P_u$) and the applied moment ($M_u$) and the axial load capacity ($P_n$) and moment capacity ($M_n$). $\phi$ is the reduction coefficient.

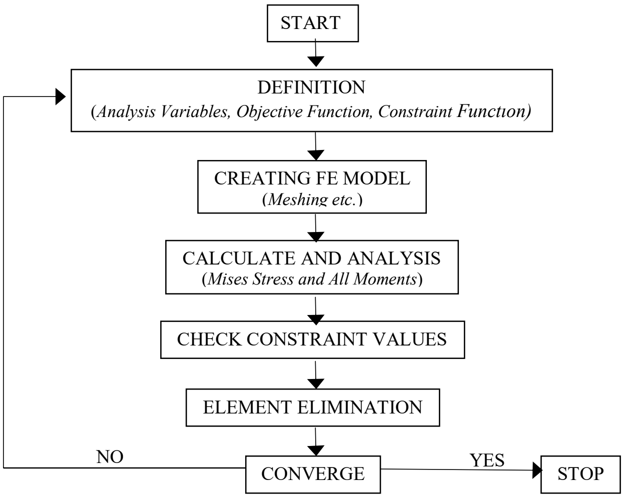
$$\mathbf{g_7 = \left(\frac{P_u}{2\phi P_n}\right) + \left(\frac{M_u}{2\phi M_n}\right) - 1 \leq 0;\ \frac{P_u}{\phi P_n} \leq 0.2} \tag{11}$$

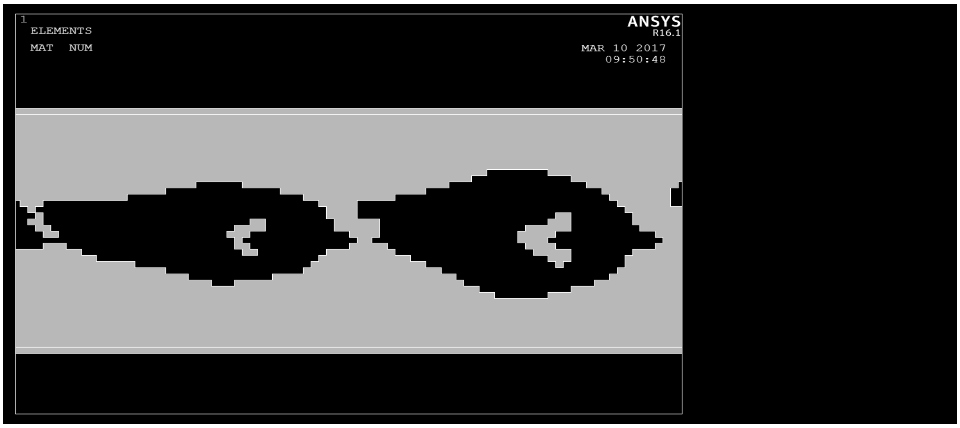
The following equations can be written for cellular beams, ignoring the effect of applied load and considering the vertical stability and the rate of change of bending moment.

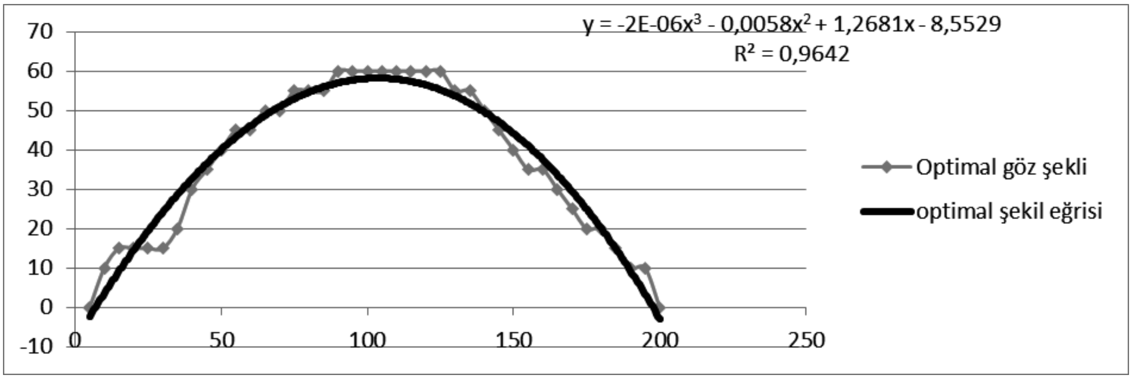
$$\begin{aligned} &\mathbf{V_{i+1} = V_i} \\ &\mathbf{M_i = T_i \times (H_s - 2x_0)} \\ &\mathbf{V_{i+1} = \frac{dM}{dx} = \frac{M_{i+1} - M_i}{S} = (T_{i+1} - T_i) \times \frac{(H_s - 2x_0)}{S}} \end{aligned} \tag{12}$$

horizontal equilibrium is;

$$\mathbf{V_h = T_{i+1} - T_i = V_{i+1} \frac{S}{H_s - 2x_0}} \tag{13}$$






Stress calculations were made between L⁄3and L⁄4, therefore the optimal eye shape corresponding to this range will be taken as reference [26].In order to determine the equation of the curves (which form the reference shape) by using curve fitting method, the shape is moved to the coordinate plane. The equation of the curve which forms the shape with $R^2$=9642 accuracy is calculated by using MS Excel program and then it is modeled again on the computer. (Figure 4-6) Thus the optimal castellated beam is obtained

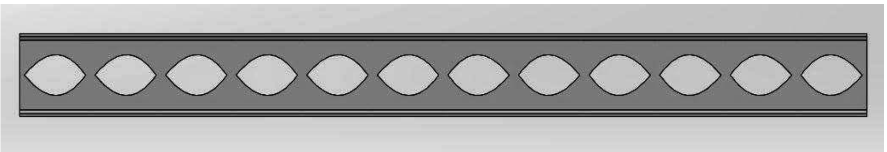


**Figure 6.** Castellated beam with optimal eye clearance and shape

## 4. COMPARISON OF WIDELY USED PERFORATED BEAMS AND OPTIMUM PERFORATED BEAM

The analysis, whose results are evaluated, is as follows (Figure 7) for all perforated beams.

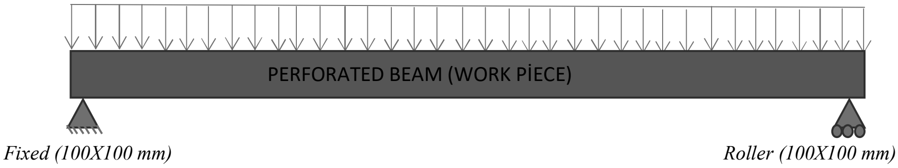



**Figure 7.** Analysis experimental design model for al perforated beams.

The simplest method for castellated beam analysis is the basic bending theory which takes the reduced web section into account when calculating the stress and deflection in beams.

The results calculated with this method may deviate significantly from the actual value due to the fact that it neglects local twist in the T-section. Vierendeel analysis is another widely used method. In this method, stress values due to local bending at shearing force in the T-section are also taken into consideration in addition to the stretching values due to bending [2].In total, 3 types of castellated beams were analyzed for this comparison. And each beam is loaded up to the limit of yield. These are the beam with a circular web opened –cellular beams, the beam with a hexagonal web opened –castellated beams, and finally the perforated beam with optimal web opened which we have obtained. As can be seen in the graph below, (Figure 8) the obtained optimal beam has the lowest internal stress value among these three.



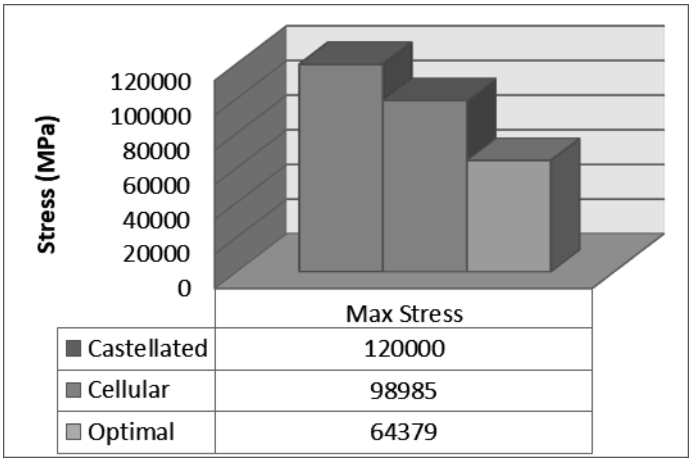



**Figure 8.** Von Mises stress levels for cellular, castellated and topology optimized beams at yield load

As is known, shear fracture is a brittle fracture type which is bluntly inconvenient. For this reason, in this study, it is aimed to develop design methods that will prevent crunching of perforated beams. The aim of the study is to produce perforated beams that reach the bending load before the shear strength and exhibit sufficiently ductile behavior. For this, it is thought that by changing the shape and numbers of the web opened on the beam, the stresses can be prevented from spreading by spreading over several holes instead of one. For both investigated beams at yield loading level, Von Mises strain is generally more uniform in stress distribution with some high localized stress concentrations in the beam optimized for openings due to the angles resulting from the openings. In contrast, stresses in the cellular tends to significantly increase in support and therefore in connection. The stresses of both investigated beams loaded at the yield limit show that the stress distribution is generally more uniform, despite some high localized (Figure 9) stress concentrations in the optimized beam due to the angles resulting from the openings. In contrast, stresses in the cellular tends to significantly increase in support and therefore in connection.

When we look at the displacement values, the castellated beam with web opened has better resistant results (Figure 10) in both vertical displacement and horizontal displacement with Vierendeel effect.



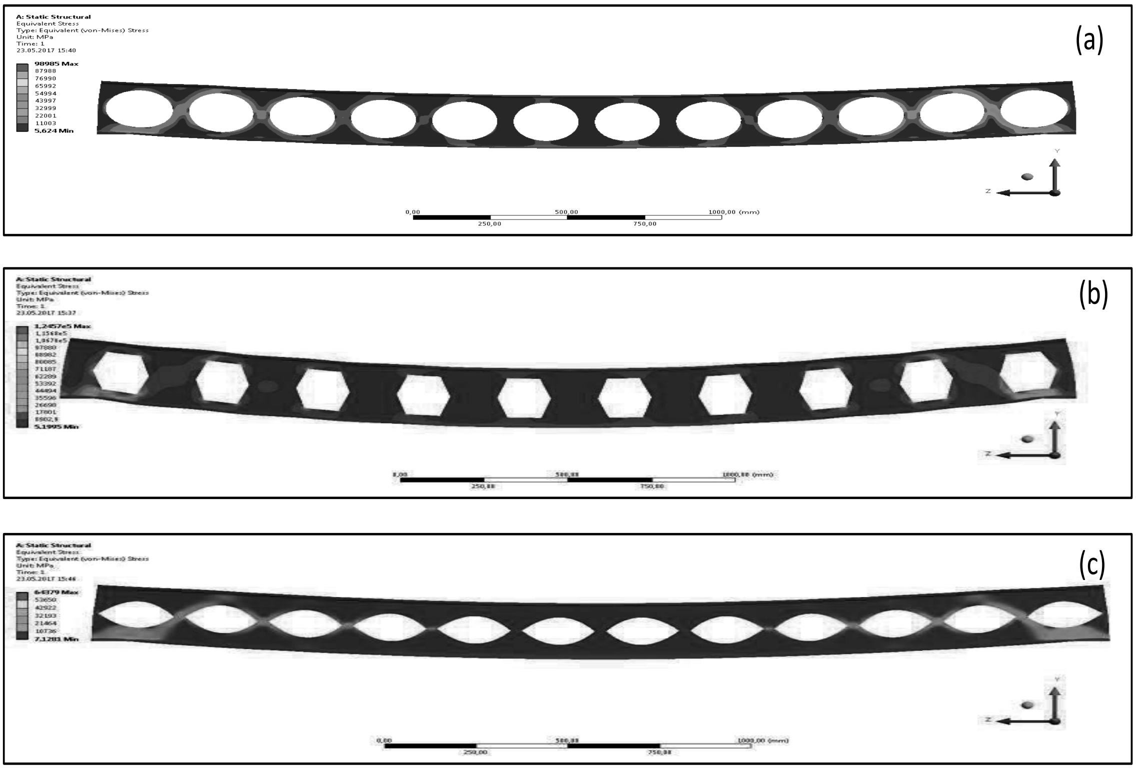



**Figure 9.** Von Mises stress plots for cellular (a), castellated (b) and topology optimized beams (c) at yield load

The last comparison subject is economy, in other words load bearing capacity per unit weight. As clearly seen, (Figure 11) the optimal beam has the highest economic value. Nowadays, the most important factor is the production cost since it determines the market share.

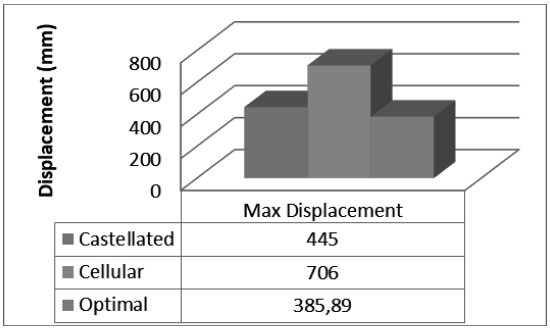



**Figure 10(a).** Displacement occurring in the horizontal axis (Vierendeel effect)

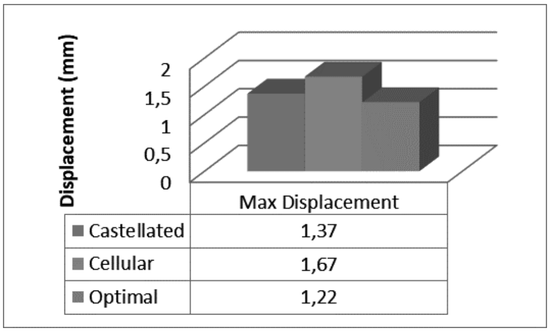



**Figure 10(b).** Displacement occurring in the vertical axis

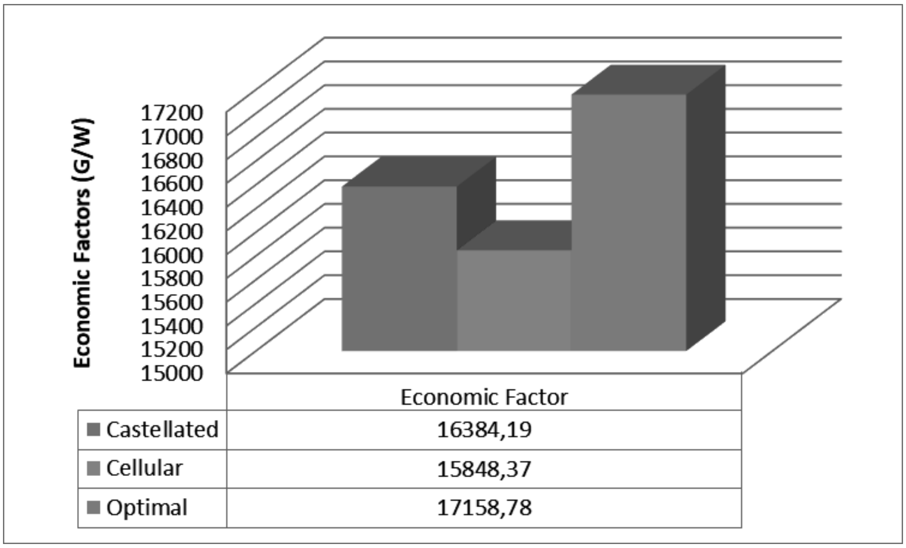



**Figure 11.** Comparison of Perforated beams based on economic factors

## 5. RESULTS AND DISCUSSION

In this study, the problem of optimal sizing for perforated beams in order to have the optimal web opened has been solved under the geometric and behavioral constraints such as where (approximately) should the web opened be.

Evolutionary optimization algorithm among topological optimization methods has been used in order to obtain the minimum weight of the optimization problem and the most optimal measures.

Comparison of the results has revealed that the obtained perorated beam with optimal web opened has performed better than other widely used beams in terms of load capacity, displacements under load and internal stresses that occur under load.

In addition, it has been seen that the load capacity that the beam can carry per its weight has also increased, so that it provides a better economic factor for the structures it will be used in.

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