Determining the Optimum Geometric Shape for Web Opening of Wide Flange Beams using Response Surface Methodology

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Abstract. In the field of civil engineering, the priority of a structural engineer is the safeness and stability of each structural element present in the structure. However, there were some concerns with regards to easy access and flexibility of the utilities such as electrical and mechanical systems. In response to these concerns, web opening was introduced to wide flanges to give way for the utilities, provided that the strength and durability of the structure will not be compensated. This study aims to obtain the optimum geometric shape of web opening for wide flange beams with regards to its performance for bending stress. The web opening on the wide flanges was designed first based on the parameters of the web opening. Then, the effects of circular, square, hexagonal and elliptical web openings were analyzed using Finite Element Analysis (FEA). Three varying support conditions in each opening case were used and analyzed using nonlinear static and nonlinear dynamic analysis in the finite element modeling software called Abaqus. During the FEA, deflection control method was used to obtain the value of force and stress upon reaching the deflection control value. Values of maximum stress and maximum force for each case were then obtained from the analysis, were used as factors for the Response Surface Methodology (RSM), which will define which shapes performed the best under specific conditions. Results obtained from RSM showed that considering value of the stress and deflection from nonlinear static and nonlinear dynamic analysis, elliptical web opening produced the largest force and smallest stress. Thus, elliptical web opening, considering bending stress, performed better compared to the other web openings.

Keywords: Web Opening, Wide Flange Beams, Finite Element Analysis, Abaqus, Response Surface Methodology

1. Introduction

Way back, being a structural engineer normally means utilizing solid sections to be used as its structural elements such as beams and girders in order to erect steel structures. Having said that, it is their responsibility to address the safeness of the structure that was built and designed and together with it, is its serviceability. However, having the two the main objective of the structural engineer in designing. It should not be forgotten that the designer also needs to consider on how to maximize the functionality of the structural system which pertains to the usage of and other uses of its structural elements. To comply with it, adjustments have been made like increasing the floor height and others had the idea of punching...
a hole through the web in order to give way for additional way of utilities. Web openings have been used in many structures especially the ones made with steel sections to comply with the functionality of the structural steel element. Commonly, the web openings of steel beams are created to improve the function of structures such as for air-conditioning ducting, electrical conduits, water supply and sanitary pipelines. Way back, web openings were created by punching the opening right at the location. However, its shows that having web openings changes the stress distribution and collapse behavior among the structural elements especially the beams and girders. Having web openings will eventually take an effect on capacity of the beam to carry load [1]

In a competitive world, with increasing cost for materials and labor, the search for the safest design economy consistent with safety and the desired life of the structure is of major importance. Members must be shaped, arranged and connected in ways that it will provide safety, economical and efficient solution to problems. Structural safety is attained through the right design, good fabrication workmanship and methods. The avoidance of any possibility of structural failure should be primary concern of the designer. Years if design experience, conditioned by both unsuccessful and successful behavior, have produced criteria that aid the choice of safe stress levels. Theses may not always produce the most economical structure; nevertheless, the overall cumulative experience in engineering design has provided designers with confidence and also let them pursue attempts to a new venturesome type of structures or members. [2]

The practice of having web openings in steel beams has been taken into consideration especially the effect of the opening on the design criteria or aspect and the capacity itself of the beam. Due to this reason, there are countries that established their national structural standards pertaining to having web openings in beams. These rules tackle the concern regarding the weakening of the beam due to web openings. However, based on what the rules shows, the rules implemented does not make the design conservative but if more studies will be done and if the parameters of the design will be adjusted, having web openings will be a lot efficient as it will become more flexible and increased economical effect. [3]

The finite element method is a numerical procedure which can model the behavior of a structure with great accuracy. Finite element modelling is normally used to deal with complicated one-dimensional, two-dimensional and three-dimensional (1D,2D,3D) geometry together with the variation among its material properties and some structural restraints. It is done by reducing the governing partial differential equations for the structure into systems of linear algebraic equations. It serves as an alternative to dealing directly with the governing partial differential equations to obtain algebraic equation systems which is then used to treat the structure in terms of its energy and work done on it. The understanding and application of the finite element method to structural system requires designers to have an idea on the vast number of concepts regarding mathematics and structural design. However, it is not needed to be really good at it or have a mastery pertaining to it but just having a knowledge regarding the limitations and good manipulative skill in the utilization and application of theorems and procedures will do a lot in the application of those in the finite element method. [4]

Response Surface Methodology (RSM) is commonly described as technique which utilizes various complex calculation techniques which helps in the optimization of the response or the output variable. This method is most likely developed in order to be suitable and compatible in creating various experimental design that will incorporate all of the independent variable that will be utilized in the modelling and also this technique utilizes all of the input data in order to produce various equations which will yield outputs based on theoretical value. Using the response surface methodology is not just by combining variables, it provides parameters for the independent variables to yield controlled variables obtained from the regression analysis. [5]
2. Methods

2.1. Design Parameters for Finite Element Analysis.
For this study, certain modes of failure is to be considered first before anything else. Three modes of failure were considered in choosing a section based on American Institute for Steel Construction (AISC) design parameters.

The chosen section should be able to pass against the following:
Local buckling

\[ \frac{b_t}{2t_t} \leq \frac{65}{\sqrt{F_y}} \]  \hspace{1cm} (1)

Web buckling

\[ p_0 - \frac{a_o}{t_o} + \frac{6h_o}{d} \]  \hspace{1cm} (2)

Lateral buckling

\[ [1 - (\frac{a_o}{t_o} + \frac{\Delta A_s}{t_w(d+2b_t)})]^2 \leq 1 \]  \hspace{1cm} (3)

After selecting the section based on the given mode of failures mentioned, design for web opening will be done by following these certain equations:

For concentrated loads, no loads should be placed above web openings unless needed otherwise bearing stiffeners are not required to prevent web crippling in the vicinity of an opening due to concentrated load if

\[ \frac{d-2t_t}{t_w} \leq \frac{420}{\sqrt{F_y}} ; \hspace{0.5cm} \frac{b}{t} \leq \frac{54}{\sqrt{F_y}} \]  \hspace{1cm} (4)

and the load should be placed d/2 from the edge of the opening or

\[ \frac{d-2t_t}{t_w} \leq \frac{520}{\sqrt{F_y}} ; \hspace{0.5cm} \frac{b}{t} \leq \frac{65}{\sqrt{F_y}} \]  \hspace{1cm} (5)

and the load should be placed d/2 from the edge of the opening and in any case the edge of an opening should not be closer than a distance d to a support

For circular openings

\[ h_o = D_o \]  for bending
\[ h_o = 0.9 \times D_o \]  for shear
\[ a_o = 0.45 \times D_o \]

D_o is the diameter of the opening

Spacing of openings

Rectangular openings

\[ s \geq h_o \]  \hspace{1cm} (6)
\[ s \geq a_o \left( \frac{V_{u}/\sigma_{y}}{1 - V_{u}/\sigma_{y}} \right) \]  \hspace{1cm} (7)

Circular Openings

\[ s \geq 1.5D_o \]  \hspace{1cm} (8)
\[ s \geq D_o \left( \frac{V_{u}/\sigma_{y}}{1 - V_{u}/\sigma_{y}} \right) \]  \hspace{1cm} (9)

wherein S = clear space between openings
2.2. Geometry of the Steel Beams and its opening

Twelve cases have been determined for this study, but before getting into the detail of those cases, it is more important to determine which section of steel beam will be used for the modelling and the geometry of the web openings for the model. In order to determine which steel section is appropriate for the study, it needs first to be based from the American Institute of Steel Construction which pertains to steel and composite beams with web opening. The sectional properties needed first to be evaluated against local buckling, web buckling, and lateral buckling. For the many sections that passed the evaluation, W12x170 (A35) was chosen for this study and the following are the properties of the said section.

| Table 1. Steel Sectional Properties |
|-------------------------------------|
| Section | Area | Depth | Web | Flange |
|         | A    | d     | tw  | tw/2   | bf   | tf   |
| W12x170 | 32258 | 356.36 | 24.38 | 12.19 | 319.28 | 39.62 |

For the modelling of the beams, the following figures below shows the typical layout for the varying support condition of each of the cases.

**Figure. 1** Simply Supported Beam Typical Design Layout

**Figure. 2** Cantilever Beam Typical Design Layout
In this study, it has two ideal concepts for the web opening, one is that the opening will be based on the code, and the other one is where utilities will pass through such that it is based for the 100 mm diameter for the web opening.

The following set of data shown on table 2 and 3 will be the one used in creating the finite element model to be analyzed in Abaqus. Results for the maximum stress and maximum deflection under deflection control method will be obtained through nonlinear static analysis and nonlinear dynamic analysis.

3. Results and Discussion
As the results were gathered, variables and responses can now be obtained in order to produce the maximum response the shape can yield. The variables to be considered in the study will be the independent variables and the dependent variables which are both essential in producing an optimum response using Response Surface Methodology. For the independent variable, there will be two variables,
which is the length of the opening and the total area of the opening caused by the hole. For the dependent variable, the one to be evaluated is the result for the maximum stress and maximum force from the analyses.

### Table 4. Result of Force and Stresses for the Circular Web Opening

| Independent Variable | Response | AISC PARAMETERS | Shape | Ao (length of opening) (m) | Total area of opening (m²) | Force (N) | Stress (MPa) |
|-----------------------|----------|-----------------|-------|---------------------------|---------------------------|-----------|--------------|
| Static Simply Supported | Circular | 0.213816 | 0.143625 | 1589003 | 370.9 |
| Cantilever Beam Circular | 0.213816 | 0.143625 | 2562493 | 415.4 |
| Fully Restrained Circular | 0.213816 | 0.143625 | 1904296 | 393.3 |
| Dynamic Simply Supported | Circular | 0.213816 | 0.143625 | 1557441 | 363.5 |
| Cantilever Beam Circular | 0.213816 | 0.143625 | 329396 | 304.4 |
| Fully Restrained Circular | 0.213816 | 0.143625 | 1942413 | 384.9 |
| 100 mm basis | | | | | |
| Static Simply Supported | Circular | 0.1 | 0.00785 | 1910585.8 | 348.7 |
| Cantilever Beam Circular | 0.1 | 0.00785 | 339174.9 | 292.3 |
| Fully Restrained Circular | 0.1 | 0.00785 | 255509.5 | 354.3 |
| Dynamic Simply Supported | Circular | 0.1 | 0.00785 | 1969052 | 365.5 |
| Cantilever Beam Circular | 0.1 | 0.00785 | 336536 | 308.0 |
| Fully Restrained Circular | 0.1 | 0.00785 | 2568495 | 354.7 |

### Table 5. Result of Force and Stresses for the Square Web Opening

| Independent Variable | Response | AISC PARAMETERS | Shape | Ao (length of opening) (m) | Total area of opening (m²) | Force (N) | Stress (MPa) |
|-----------------------|----------|-----------------|-------|---------------------------|---------------------------|-----------|--------------|
| Static Simply Supported | Square | 0.213816 | 0.182869 | 1156507.3 | 334.2 |
| Cantilever Beam Square | 0.213816 | 0.182869 | 244244.7 | 405.5 |
| Fully Restrained Square | 0.213816 | 0.182869 | 1423344 | 399 |
| Dynamic Simply Supported | Square | 0.213816 | 0.182869 | 1483556 | 363.5 |
| Cantilever Beam Square | 0.213816 | 0.182869 | 388158.8 | 303.7 |
| Fully Restrained Square | 0.213816 | 0.182869 | 1572831 | 394.2 |
| 100 mm basis | | | | | |
| Static Simply Supported | Square | 0.1 | 0.01 | 1909393.8 | 337 |
| Cantilever Beam Square | 0.1 | 0.01 | 338377.3 | 290.8 |
| Fully Restrained Square | 0.1 | 0.01 | 2563676.5 | 347.4 |
| Dynamic Simply Supported | Square | 0.1 | 0.01 | 1964636 | 350.4 |
| Cantilever Beam Square | 0.1 | 0.01 | 318748.8 | 306.6 |
| Fully Restrained Square | 0.1 | 0.01 | 2541516 | 347.4 |

### Table 6. Result of Force and Stresses for the Hexagon Web Opening

| Independent Variable | Response | AISC PARAMETERS | Shape | Ao (length of opening) (m) | Total area of opening (m²) | Force (N) | Stress (MPa) |
|-----------------------|----------|-----------------|-------|---------------------------|---------------------------|-----------|--------------|
| Static Simply Supported | Hexagon | 0.213816 | 0.16 | 1463218.3 | 365.2 |
| Cantilever Beam Hexagon | 0.213816 | 0.16 | 331673.8 | 303.7 |
| Fully Restrained Hexagon | 0.213816 | 0.16 | 1797450 | 386.5 |
| Dynamic Simply Supported | Hexagon | 0.213816 | 0.16 | 1483556 | 363.5 |
| Cantilever Beam Hexagon | 0.213816 | 0.16 | 3881558.8 | 303.7 |
| Fully Restrained Hexagon | 0.213816 | 0.16 | 1815760 | 382.5 |
| 100 mm basis | | | | | |
| Static Simply Supported | Hexagon | 0.1 | 0.00866 | 1898844.4 | 346.9 |
| Cantilever Beam Hexagon | 0.1 | 0.00866 | 339055.9 | 293 |
| Fully Restrained Hexagon | 0.1 | 0.00866 | 2567842.8 | 349.4 |
| Dynamic Simply Supported | Hexagon | 0.1 | 0.00866 | 1957815 | 355.9 |
| Cantilever Beam Hexagon | 0.1 | 0.00866 | 318164.9 | 309 |
| Fully Restrained Hexagon | 0.1 | 0.00866 | 2546436 | 349 |
Table 7. Result of Force and Stresses for the Ellipse Web Opening

| AISC PARAMETERS | Shape       | Ao (length of opening) (m) | Total area of opening (m²) | Force (N)   | Stress (MPa) |
|-----------------|-------------|----------------------------|---------------------------|-------------|--------------|
| Static          | Simply Supported | Ellipse | 0.160362 | 0.215437 | 1679468.6 | 356.6        |
| Cantilever Beam | Ellipse     | 0.160362 | 0.215437 | 335962.5 | 290          |
| Fully Restrained| Ellipse     | 0.160362 | 0.215437 | 2123735  | 379.7        |
| Dynamic         | Simply Supported | Ellipse | 0.160362 | 0.215437 | 1692968    | 340.8        |
| Cantilever Beam | Ellipse     | 0.160362 | 0.215437 | 32954.4  | 306.1        |
| Fully Restrained| Ellipse     | 0.160362 | 0.215437 | 2143256  | 375.7        |

100 mm basis

| Static          | Simply Supported | Ellipse | 0.1005  | 0.084615657 | 1860529.1 | 340.1        |
| Cantilever Beam | Ellipse     | 0.1005  | 0.084615657 | 338548.1  | 292.3        |
| Fully Restrained| Ellipse     | 0.1005  | 0.084615657 | 2487999.8 | 356.6        |
| Dynamic         | Simply Supported | Ellipse | 0.1005  | 0.084615657 | 19242184  | 353.7        |
| Cantilever Beam | Ellipse     | 0.1005  | 0.084615657 | 355395.7  | 309.2        |
| Fully Restrained| Ellipse     | 0.1005  | 0.084615657 | 2509804   | 355.3        |

Table 8. Summary of Optimization Results for Force and Stress

| Shape          | Force (kN) | Stress (Mpa) |
|----------------|------------|--------------|
| Circular       | 1262.307   | 372.0067     |
| Square         | 1327.26    | 343.4939     |
| Regular Hexagon| 1430.714   | 341.4148     |
| Vertical Ellipse| 1579.515   | 334.5333     |

4. Conclusion

The primary objective of this study is to explore the effect of having varying geometric shape for the web openings of wide flange beams and determine which will yield the optimum performance for the bending stress. This may be obtained by subjecting the wide flange beams with different geometric shapes given that the beam will also be under varying support conditions. The beam will then be subjected to nonlinear static analysis and nonlinear dynamic analysis wherein the maximum stress and maximum force will be obtained through the use of the deflection control method wherein the stress and force experienced by the section will be obtained when the deflection limit is attained. Values of the length of opening and total area of opening will then be used as independent variables while the values of the maximum force and maximum stress will serve as the response to the RSM. With those procedures, it will then yield that the ellipse performed the best under given conditions such that upon optimization, the ellipse yielded the highest value of force, which is 1579.515 kN, to attain the limit for deflection control and the same time, it shows that it also has the least stress experienced, which is 334.5333 MPa compared to the other geometric shapes that were given. These results only conclude that the remaining area on the web does not determine the overall capacity of the beam, thus it depends on the geometric shape that was used for the web opening.
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