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Research Article

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Parametric Study on the Flexural Behavior of Cellular Beams under Uniform Loading

Ofonime Harry*, Joseph Samuel

*Department of Civil Engineering, University of Uyo, Nigeria

Abstract The use of web perforated beam such as cellular and castellated beams in construction has been very popular due to its numerous advantages such as reduced weight to depth ratio, less consumption of material, higher bending stiffness and reduction in storey height, thanks to the presence of holes/openings where service pipes can be passed. In this paper, the effect of two key parameters on the behavior of cellular beam subjected to uniform load is investigated. These parameters are; ratio of spacing between openings to the diameter of opening (S/a_o) and the ratio of overall depth of beam to the diameter of opening (H/a_o). A total of 6finite element models were developed using a 4-node shell element with reduced integration. Three of these models were used to investigate the effect of S/a_o on the behavior of beam, with S/a_o ratio ranging from 1.26 to 1.60. The other three models were used to investigate the effect of H/a_o with the ratio ranging from 1.27 to1.67. The result showed that for beam with $S/a_o>1.47$, the behavior of beam and load capacity is less affected by $S/a_{o.}$ From the second set of model, it is noted that the load capacity of the beam is directly proportional to the ratio of H/a_o every other parameters being the same.

Keywords Web perforated beam, cellular beams, castellated beam, spacing between openings

Introduction

Researchers in the built industry have explored ways of constructing buildings that are smart and less costly compared to the traditionally known materials and geometry. One of such innovations is the use of web perforated beams in construction. Web perforated beams are beams with well-defined openings within the web portion of the beam. The commonly used types are beam with circular and hexagonal openings. Web perforated beams made with circular openings are called cellular beam while that with hexagonal openings are called castellated beam. The importance of these beams are seen in the construction of high rise buildings and stadia due to their weight-to-strength ratio, aesthetic appearance and its ability to integrate service pipes within the depth of beam [1] which leads to reduction in storey height and cost of construction. Web expanded beam in comparison with solid beam (parent beam), has a higher shear bending stiffness and uses less steel [2, 3].

Extensive study about the behavior of web perforated beams with circular and hexagonal openings exist in literature [4-6]. Also, studies on beams with novels opening aimed at optimizing the existing standard sections have been investigated [7]. Ref [8] studied the behavior of castellated beam with hexagonal openings, subjected to two point loads which was equidistance to the support. Parameter investigated in their study was the ratio of opening spacing to the depth of beam. They concluded that castellated beam with web opening of 0.6 times the depth of beam behaved satisfactorily.

In a related study, the load carrying capacity of optimally designed castellated beams with different number of holes was investigated using finite element models. The beam was subjected to point load at the midspan [9]. It was observed that even for short length of beam, torsional buckling was dominant and Vierendeel mode of failure was observed for beams with point load located above the opening while torsional web buckling was observed when the load was place between two openings.

Many researches in the literature focused on web perforated beam with circular and hexagonal openings subjected to concentrated load. In building construction, web perforated beams are used as secondary beams. These beams carries uniformly distributed loads from the floor slab. The behavior of web perforated beam under this type of loading is seldom studied. Moreover, the effect of variation in the opening spacing on the load capacity and displacement behavior is not fully understood. To address this questions, this paper present a numerical investigation into the effect of variation in ratio of spacing of opening to diameter of opening (S/a_o) and ratio of depth of beam to the diameter of opening (H/a_o) on the flexural behavior of simply supported perforated beam subjected to uniform load.

Analysis and design of cellular beams

The procedure involved in manufacturing cellular beams includes cutting the solid beam in a certain pattern as shown in Figure 1, and reassembling them by welding, so that they have a deeper section compared to the parent beam [10]. The presence of hole in the beam affect the structural performance of the beam. Therefore these holes must be arranged in a way that does not affect the structural performance of the beam. The guidelines given by [Ref 11] are based on experiment and field experience.

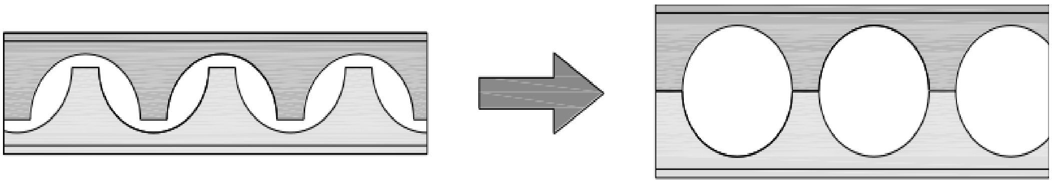


Figure 1: Fabrication of cellular beams [Ref 10]

These guidelines are given as follows;

$$1.25\ a_o < H < 1.75\ a_o \tag{1}$$

$$1.08a_o < S < 1.75\ a_o \tag{2}$$

$$a_o \leq 0.8a_o \tag{3}$$

$$e \leq 0.4a_o \tag{4}$$

The above expression is slightly modified in the recommendations given Ref [12] as follows;

$$1.25\ a_o \leq H \leq 1.75\ a_o \tag{5}$$

$$1.2\ a_o \leq S \leq 1.70\ a_o \tag{6}$$

where,

a_o = depth of opening provided

H = overall depth of Beam

S= center to centre spacing between two opening

e= clear distance between two opening

b= width of flange

t_f = thickness of flange

t_w = thickness of web

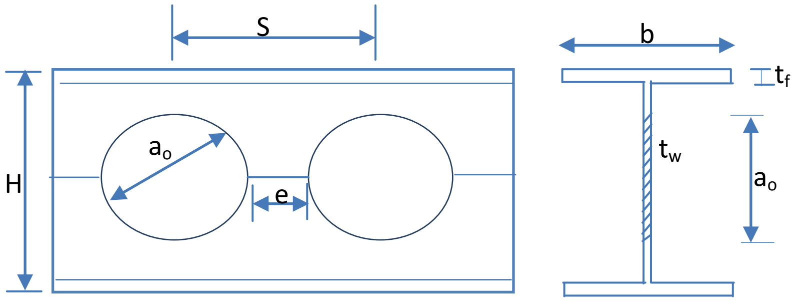


Figure 2: Typical section of a cellular beam

Methodology

Six (6) different models were created in this study. Three of the models were used to investigate the effect of S/a_o on the behavior of cellular beam while the other three models were used to investigate the effect of H/a_o on the beam. The different ratios of S/a_o and H/a_o are within the recommendation in ref [12] and Equation (5) and (6) as shown in Table 1.

Table 1: Geometric properties of different models considered in the study

Model ID	Length (m)	T_f (mm)	t_w (mm)	a_o (mm)	S_o (mm)	H (mm)	S/a_o	H/a_o
A	3	7.20	5.48	150	188.5	250	1.26	1.67
B	3	7.20	5.48	150	220	250	1.47	1.67
C	3	7.20	5.48	150	240	250	1.60	1.67
D	3	7.20	5.48	150	240	190	1.60	1.27
E	3	7.20	5.48	150	240	220	1.60	1.47
F	3	7.20	5.48	150	240	250	1.60	1.67

Numerical models of the beams were created using ABAQUS finite element code. The beams were modelled with a 4-node shell element with reduced integration point (SR4). Material properties for the steel were; modulus of elastic of 200,000N/mm^2, yield strength of 275N/mm^2 and poison ratio of 0.3. Prior to the analysis, a mesh sensitivity analysis was carried out to determine a mesh size that is computationally efficient. The result of sensitivity analysis shows that a mesh size of 15mm is adequate for the study.

Boundary condition was applied to the models to simulate a simply support condition. To achieve this, degrees of freedom (U_x, U_y and U_z) of line nodes at the support section (point A in Figure 3) were set to zero. Support nodes at the other end were set to zero in U_x and U_y direction but not U_z-direction to avoid the development of axial forces from the restrained nodes. Figure 3 shows details of boundary condition applied to the models while Figure 4 shows the full finite element model of beam A.

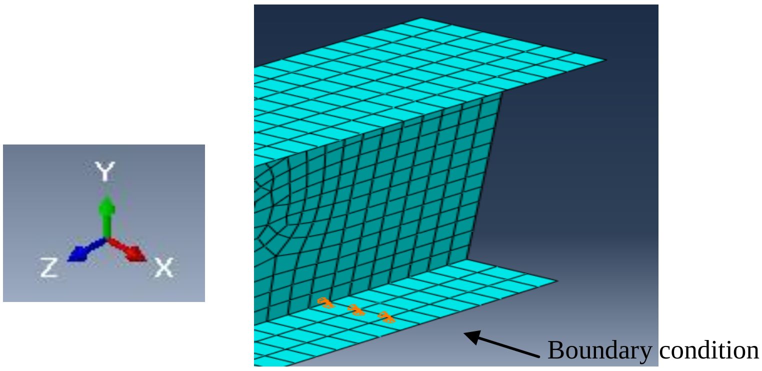


Figure 3: Boundary conditions applied in FE models

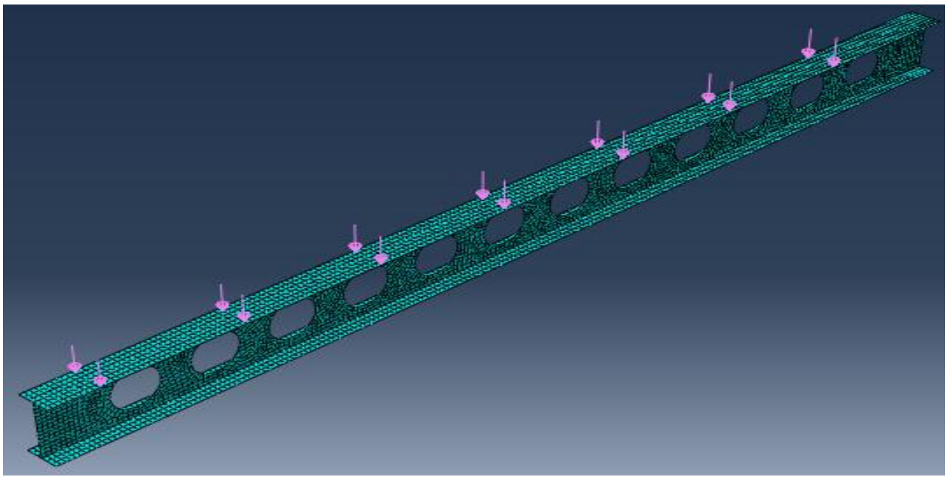


Figure 4: Model type a showing the mesh discretization and loading

Quasi static analysis was performed using dynamic implicit available in ABAQUS. This solveris adequate for quasi static applications in which the final static response is only required and inertia forces introduced only to regularized the unstable behavior [13]. Time increment can either be automatic or fixed. In automatic increment, time increment is decided by the solver while in the fixed increment, a user defined time increment is specified. The disadvantage of fixed time increment is that, if the step time reduces below the stipulated fixed time the analysis is aborted. In this study, the fixed time increment was adopted so that a comparative analysis can be performed between the result of different models at a given time and load level. The time increment was taken to be 0.001 and the analysis was performed for one second (1s) giving a total of 1000 output steps. Pressure loads representing uniformly distributed load was applied to the flange in the downward direction as shown in Figure 4 until failure of the beam.

Result and Discussion

Effect of S/a$_o$

The load-displacement response for models A,B and C is presented in Figure 5. From this plot, it is seen thatmidspan displacement increased expondentially between the initiation of yielding and the attainment of maximum load capacity in model A compared to model B and C. This could be attributed to the closer spacing of holes. For beam with S/a$_o$ of 1.47 or less, the beam capacity is reduced compared to beam with S/a$_o$ greater than 1.47.

Displacement of the beam along its length at two selected time step is further studied. The applied load corresonding to these time steps are 20KN/m and 36KN/m. It can be seen that at the load of 20KN/m, all the models were within elastic static, thus the displacement is very small. Furthermore, there is only mininal difference in displacement along the beam in models B and C at load level of 20 and 36KN/m.This further correlate with the load-dispalcement plot in Figure 5.

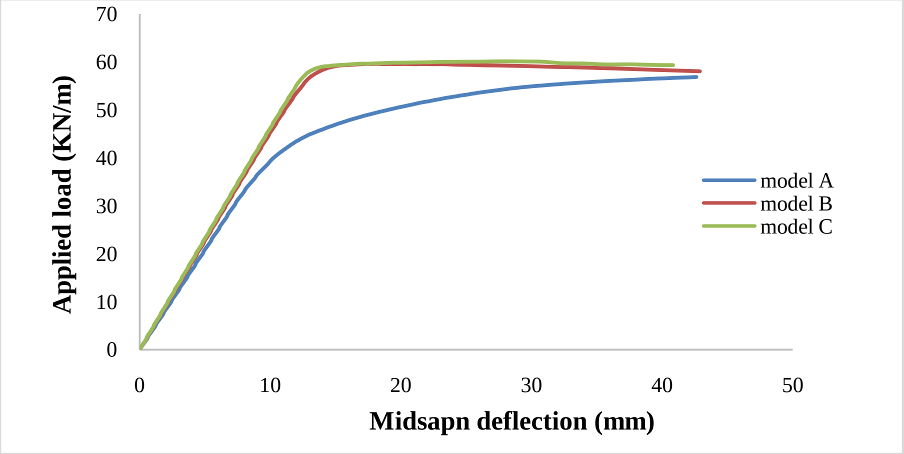


Figure 5: Effect of S/a$_o$ on load-displacement behavior

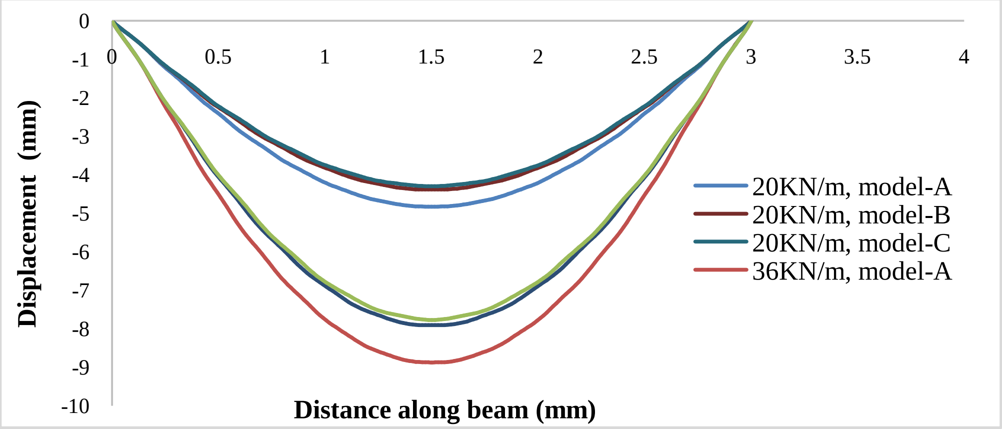
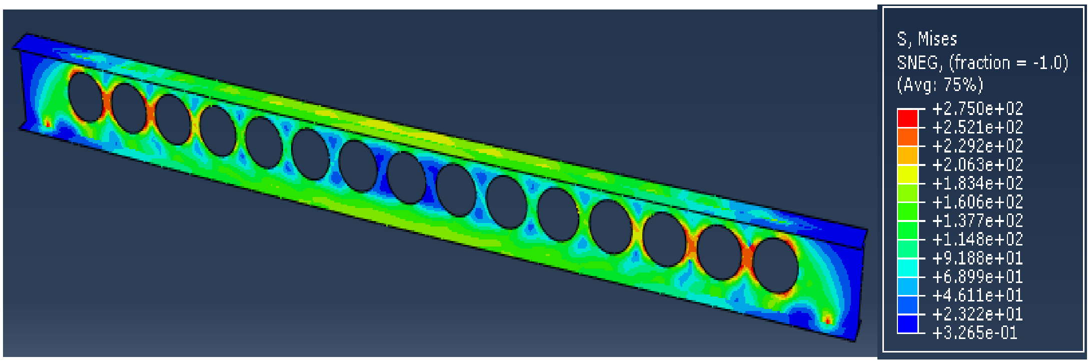
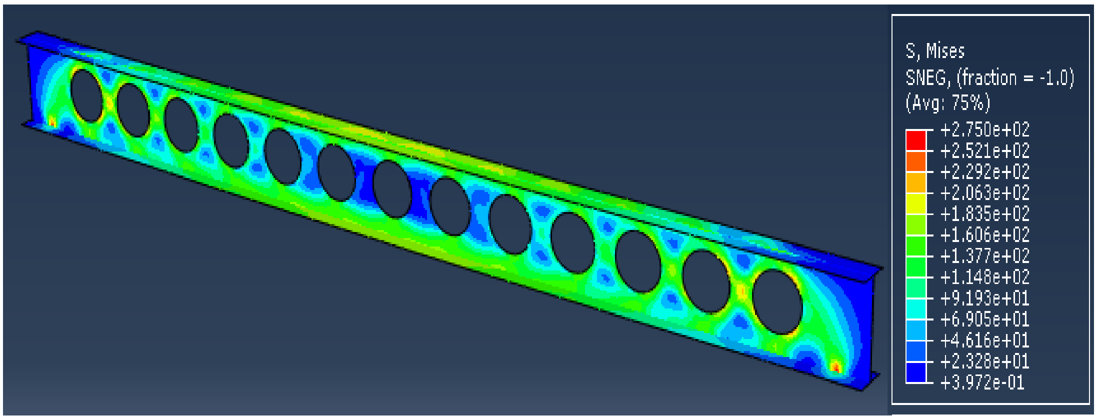


Figure 6: Effect of S/a$_o$ ratio on displacement along the beam at uniformload of 20KN/m and 36KN/m

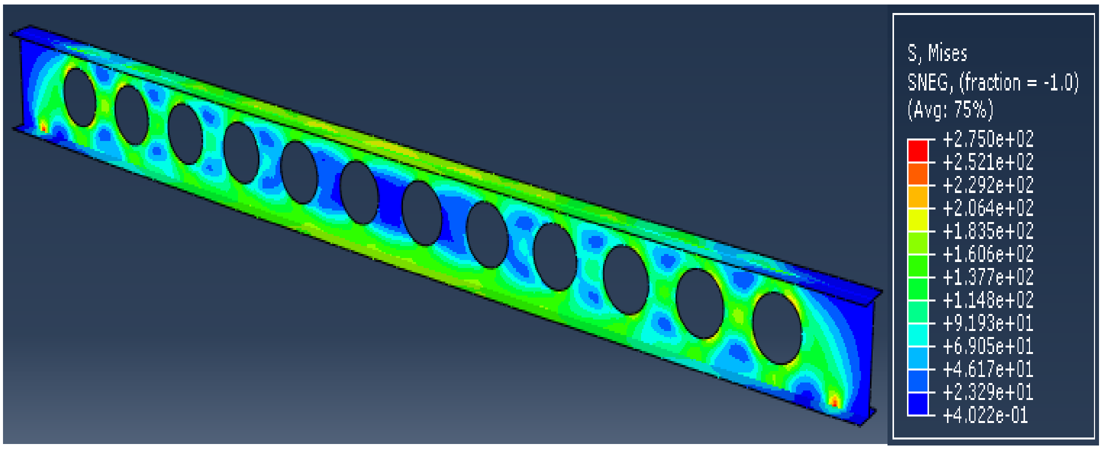
The contour plot of stress distribution in models A, B and C at a load of 36KN/m is shown inFigure 7. In all the models,stress concentrated within the edges of the holes near the support section. Due to this high stress concentration, the end section of model A entered it yield stage with stresses in flanges still remained within elastic range. This behavor is slightly different from solid-I-beam where flanges at the critical section of the beam yield first before the web. The lowest stress is observed within the middle section of the beam (two middle holes) with a stress value of between 0.33 and 23.22N/mm^2.



(a) Model A



(b) Model B



(c) Model C

Figure 7: Stress distribution in models A, B and C at a load of 36KN/m

Effect of H/a$_0$ on load capacity

The load-displacement plot of models D, E and F is shown in Figure 8. Comparing this result with models A, B and C, there is remarkable difference in load capacity as the ratio of H/a$_0$ increases. For instance, the load capacity in model F is almost twice that of model D. It can be concluded that increase in load capacity is proportonal to the H/a_o ratio. Thus, for beam with a given span, flange and web thickness, the load capacity is minimally influenced by S/a_o but increases proportibally with H/a_o.

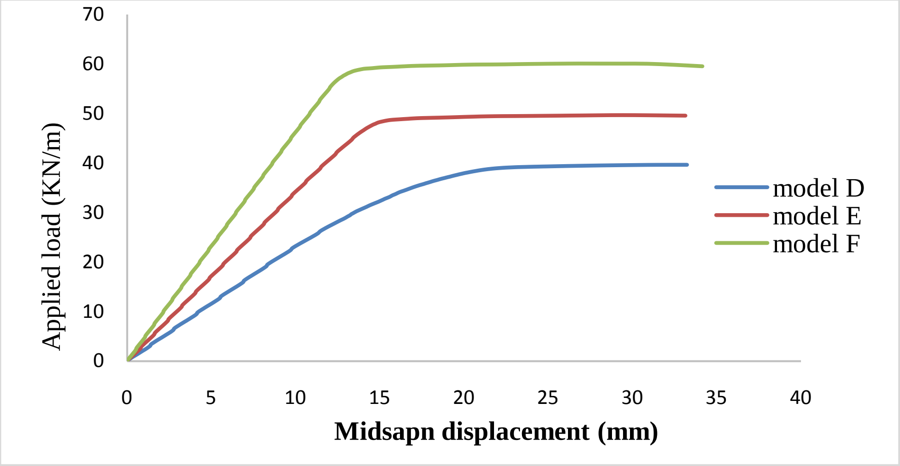


Figure 8: Effect of H/a_o on load-displacement behavior

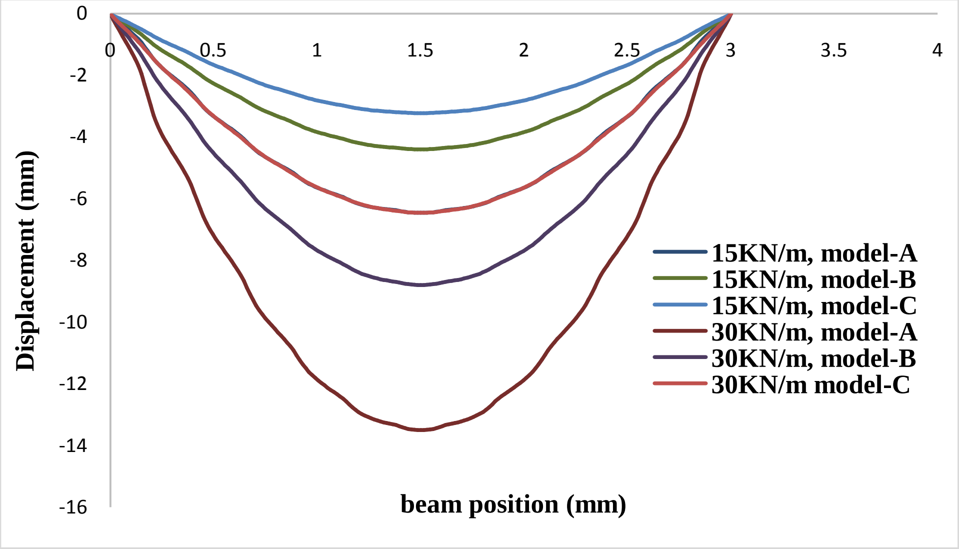
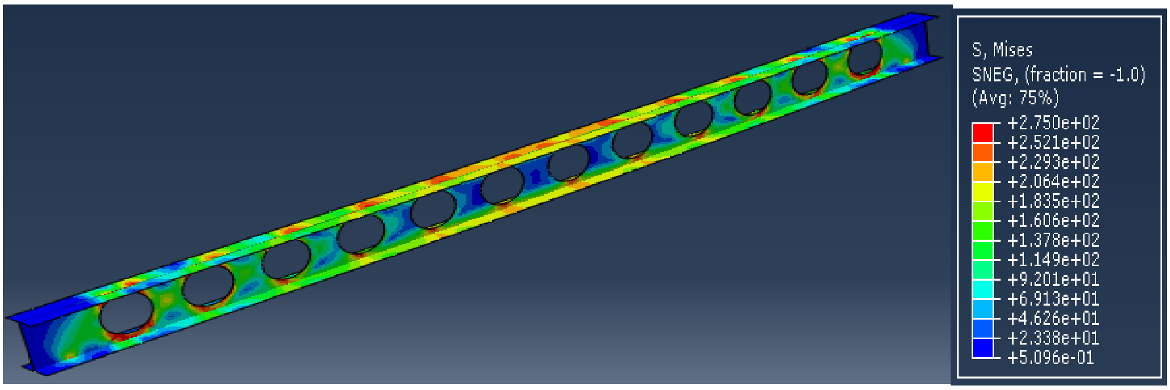


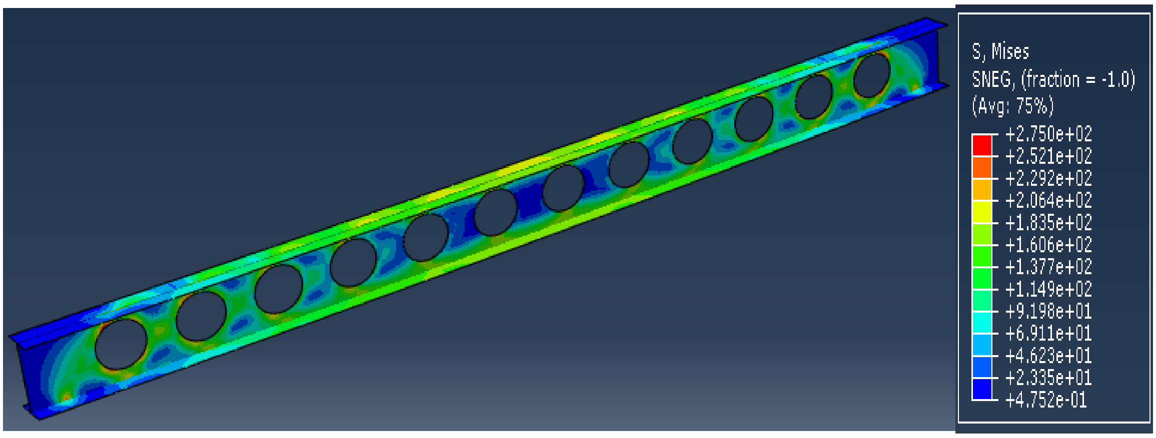
Figure 9: Effect of H/a_o ratio on displacement along the beam at uniform load of 15KN/m and 30KN/m

The displacement along the length of the beam is also shown in Figure 9. The displacement increases with increase in H/a_o ratio. The displacement along the length of beam in model C at a load of 30KN/m coincided with the displacement of model A at load of 15KN/m. Comparing Figure 9 with Figure 6, it can be observed that for a given magnitude of uniform load, beam displacement is influenced by ratio of H/a_omuch more than the ratio of S/a_o.

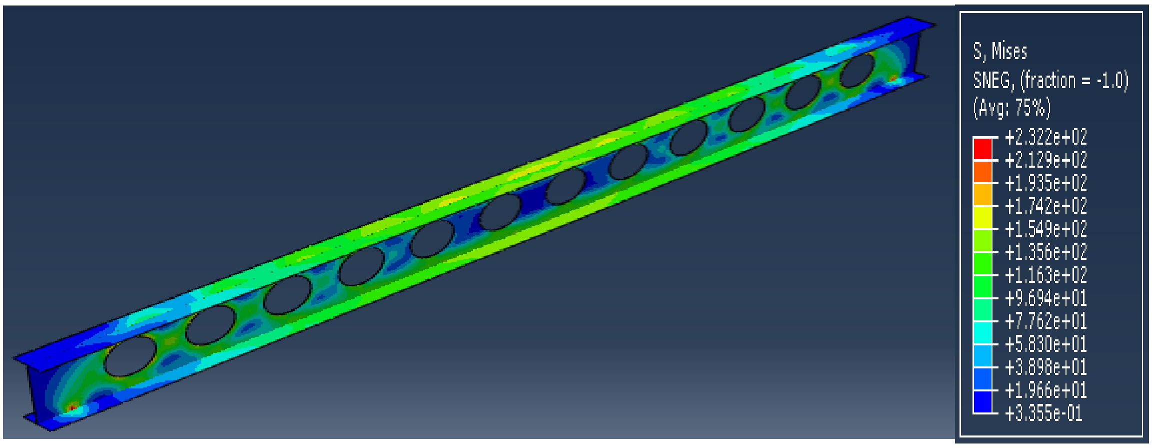
The contour of stress distribution plotted in Figure 10 shows that at load level of 30KN/m, model C was still in elastic stage while part of beam in model A and B were at the yield stage. In all the models, the least stressed area of the beam is the spacing between the circular opening at the midspan of the beam.



(a) Model A



(b) Model B



(c) Model C

Figure 10: Stress distribution in models D, E and F at a load of 30KN/m

Conclusion

This paper presented a parametric study on the behaviour of castellated beam. The parameters investigated were; ratio of spacing of perforation to the diameter of opening (S/a_o) and height of beam to diameter of hole (H/a_o). From the result of this study the following conclusion can be deduced.

1. The load capacity and displacement of cellular beam is influenced by the ratios of S/a_o and H/a_o but the effect of S/a_o is small compared to the effect of H/a_o, every other parameter being the same.
2. Load capacity is directly proportional to the H/a_o ratio.
3. Unlike solid I-beam where yielding progresses from flange to web, yielding in cellular beam may occur in some highly stress area of the web such as edges of the openings.
4. The behavior of cellular beam can be accurately modelled with finite element code.

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