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AN INNOVATIVE TECHNIQUE TO REDUCE COMPUTATIONAL EXPENSE AND TIME FOR SIMULATION OF STRUCTURAL EFFECT OF A VOID

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Abstract-Presence of small features can cause significant amount of increase in the amount of meshing effort and computational expense. Small features increase the complexity of the physics considerably without appreciably increasing the stiffness of the structure. Small features can cause significant stress concentration requiring a local mesh refinement to match the small feature. While in ductile materials, the stress concentration can usually be ignored, this phenomenon requires a careful evaluation in brittle materials like cast iron. In such cases sub-modeling can be used effectively for simplification of the problem. A stress based approach may not be enough in this case and a fracture mechanics evaluation may be necessary. In this work, a method is devised to decrease the computational expense and also decrease the meshing effort. The effectiveness of the method is demonstrated in a case study. Further, a fracture mechanics evaluation of the cast iron girder with a spherical void is carried out.
Key words: Sub modeling, small features, computational expense, void.

1. INTRODUCTION

Cast Iron girders are used in supporting gantry cranes. These structures experience bending and compressive loads during their service. Since the structures are brittle, the stress concentration affects the strength of the structures significantly. The presence of voids in these structures can cause a decrease in the strength of the girders. The presence of voids causes an increase in the mesh refinement requirements due to the small size of the void and also an increase in the computational expense of the analysis.

2. ANALYTICAL CALCULATIONS

The cast iron girder used in the gantry crane system can be considered a cantilever beam [1]. The stresses are maximum when the weight is at the centre of the girder.

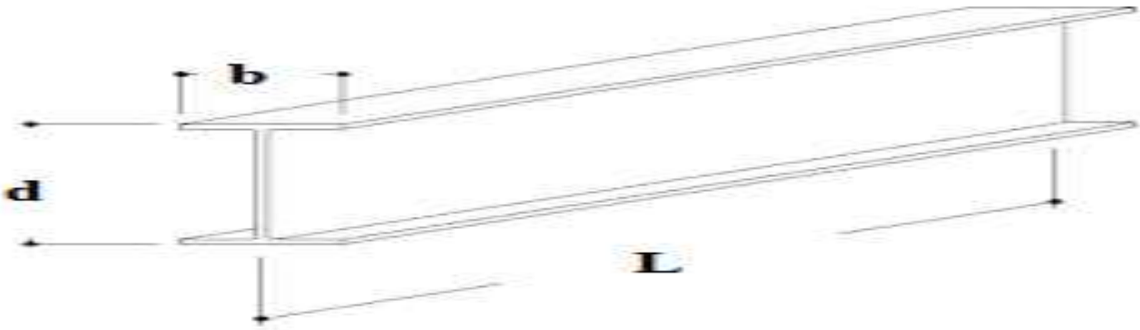

Fig. 2.1 Girder Beam

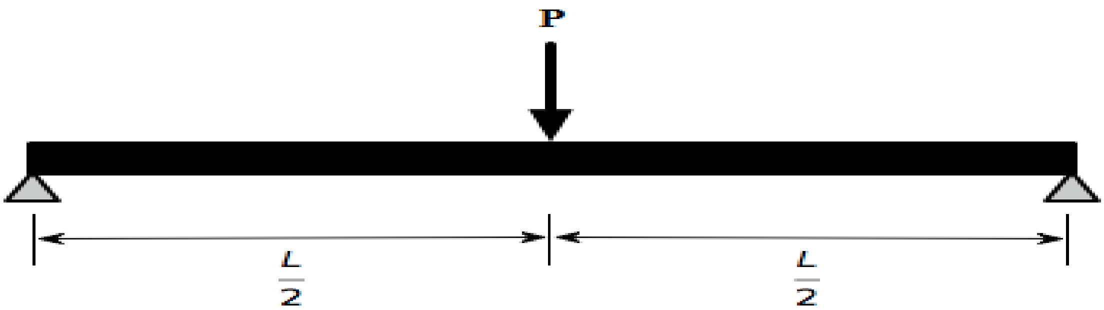

Fig. 2.2 Simply Supported Beam

The maximum stress induced [2] is σ = MY/I
Where,
M is the bending moment at the centre
Y is the distance of the outermost fiber of the beam cross section from the neutral axis.
I is the second moment of inertia of the section.
M = P*L/2 = 0.1 G N.mm
Where,
P is the load = 10 Tons
L is the supported length of the girder = 2 m

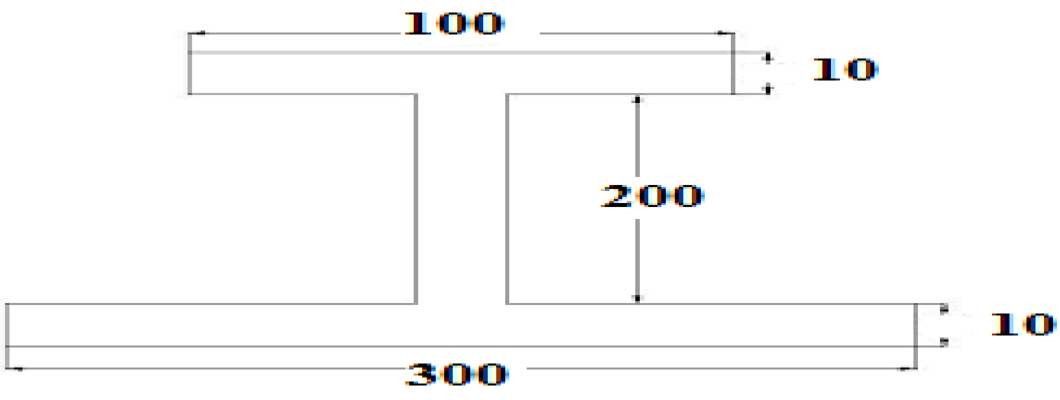

Fig. 2.3 Girder Beam Section

Y= 133 mm
I= 15.6 * 10^6 mm^4
Nominal stress induced = 52 MPa
The stress induced in case of a void of diameter 1mm = Stress concentration factor * nominal stress [3]
The stress concentration factor [1] = 2.2
The concentrated stress = 114.4 MPa.
The deflection [4] is = $pL^3/48EI$ = 1.45 mm

3. FINITE ELEMENT ANALYSIS

3.1 Geometry and Boundary Conditions

The geometry, loads and boundary conditions are shown in fig. 3.1. The girder is simply supported at the ends and the load 100000N acts at the centre.

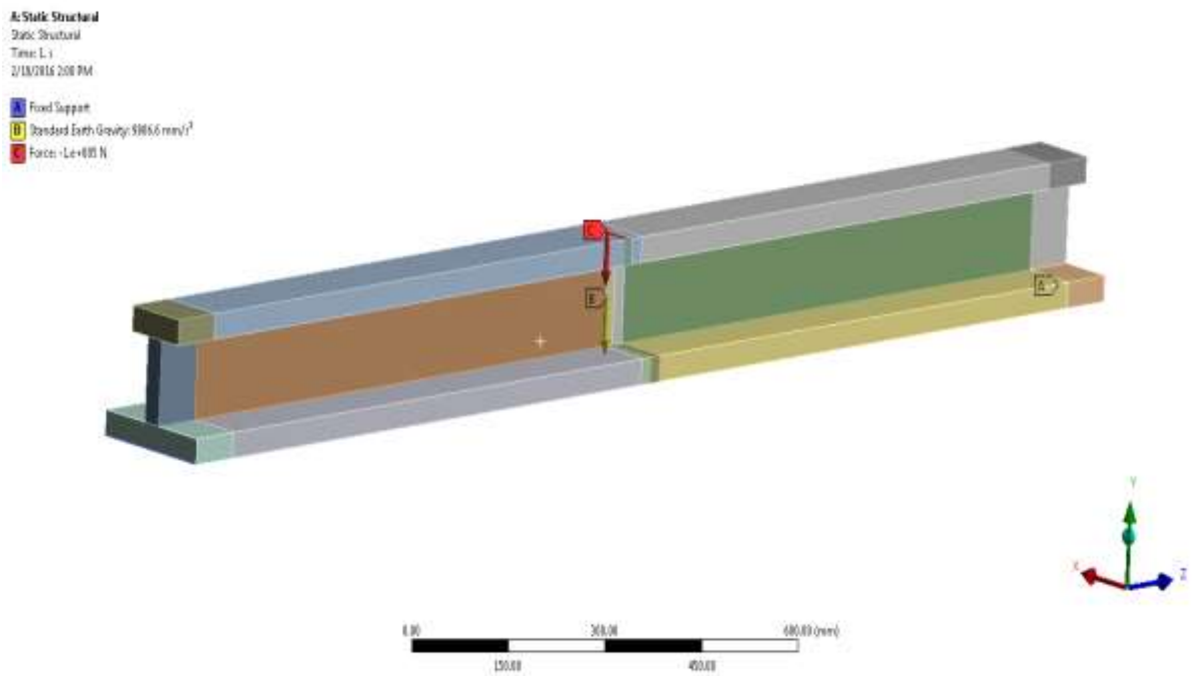

Fig. 3.1 CAD Model of the Girder Beam

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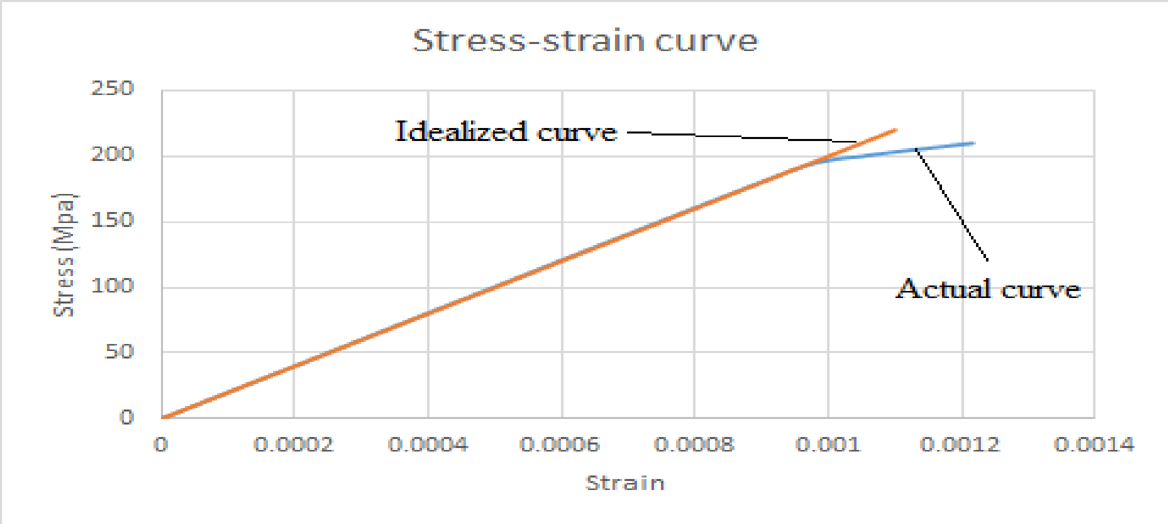

Fig. 3.2 Stress- Strain Curves

The actual and idealized stress-strain curves are shown in the figure. The stress strain curve is assumed to be a straight line for this linear structural analysis along with the assumption of small displacements.

3.2 Mesh

The converged mesh of the structure is shown in fig. 3.3.

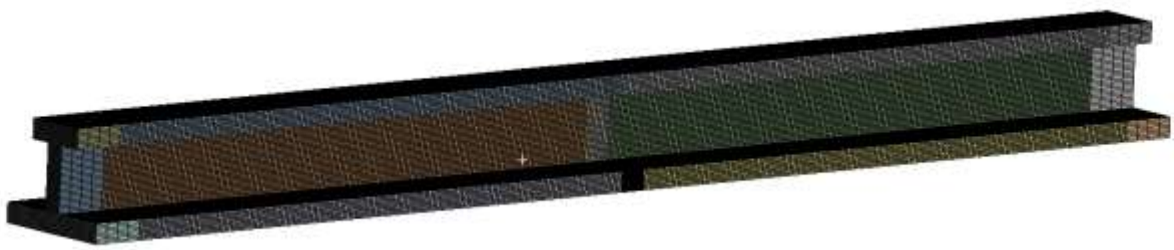

Fig. 3.3 Meshed Model

3.3 Solution Convergence

The solution is checked for convergence by running the solution for successively finer meshes till convergence is achieved [5]. The convergence plot is shown in fig. 3.4.

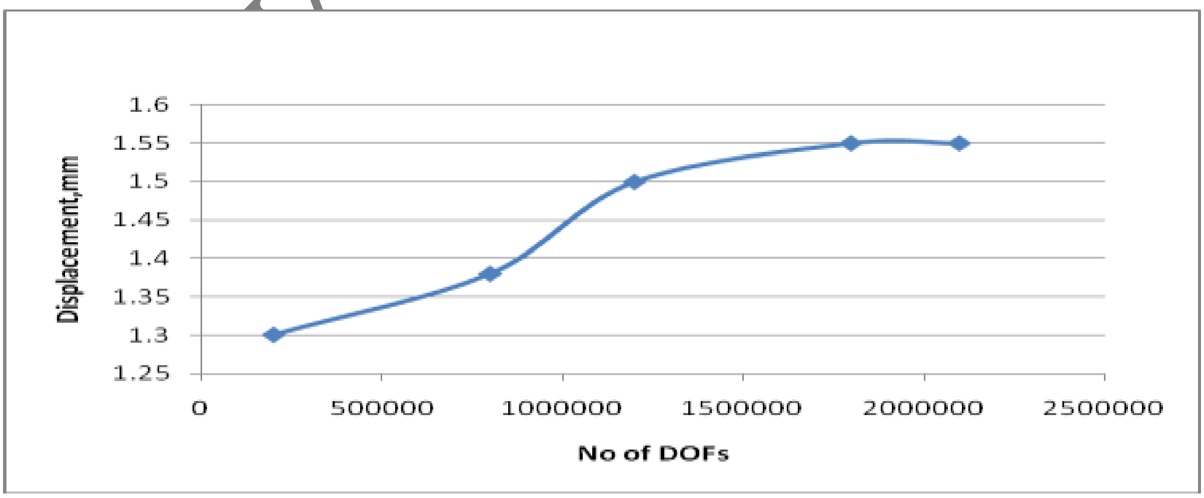

Fig. 3.4 Convergence Plot

3.4 Results

The converged solution for the iron girder model with void is shown in fig. 3.5 (displacement plot) and fig. 3.6 (maximum principal stress plot).

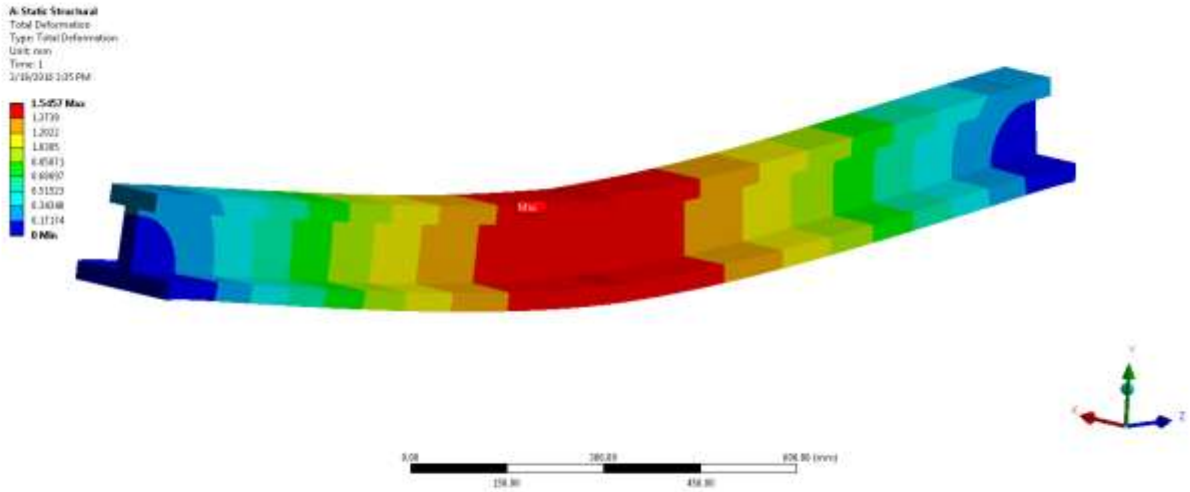

Fig. 3.5 Results- Deflection with Void

Fig. 3.6 Maximum Principal Stress in the Full Model with Void

Since the analysis is linear, the Stress-load plot is also linear. Thus the value of stress at any value of load can be found without resorting to recalculation by just extrapolation.

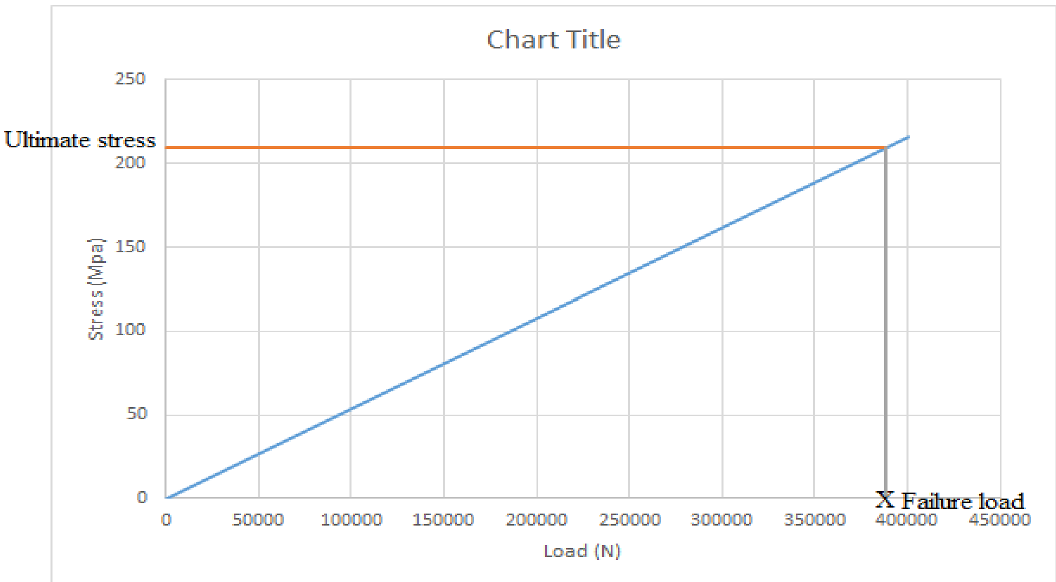

Fig. 3.7 Load-Displacement Plot

The ultimate strength of cast iron σult = 210 MPa
Since load is proportional to stress, σ = c.P
Where c is the proportional constant and P is the load in m.
Therefore P = σ/c
At a load of 0.1 MN, the nominal stress = 54.05 MPa
⇨ c = 54.05/0.1 = 540.5 MPa/MN
The load at which the maximum principal stress reaches the ultimate stress, Pult = Sult/c
= 210/540.5 = 0.388529 MN = 388529 N

The concentrated stress at 388529N is = $\frac{\sigma}{\sigma nom} * \sigma ult$ = 97.904/54.05*210 = 380.3856 MPa

It may be noted that the maximum principal stress at the Pult is greater than the ultimate stress but it may not result in rupture if the stress intensity factor is less than the critical stress intensity factor, Kc.
The critical stress intensity factor for cast iron = 10MPa√m
The induced stress intensity factor [6], K = σnom*√(π.a) = 11.77 MPa√m
Where a is the diameter of void in m

Therefore the failure stress as per fracture mechanics, σf = $\frac{Kc}{K} * \sigma ult$ = 178.41 MPa

The concentrated stress when σnom equals 178.41 MPa = 97.904/54.05*178.41 = 323.17 MPa
The failure load = 323.17/540.5= 0.597908 MN = 597908 N
Even though the stress is greater than the ultimate strength, the structure continues to withstand load because of fracture mechanics energy considerations. The maximum principal stress crosses ultimate stress at a load of 388529 N, the girder continues to withstand load till load reaches 597908 N.

4. INNOVATIVE TECHNIQUE

The presence of the void does not affect the stiffness to any significant extent. Thus the displacement results are not affected by the absence of void. Accurate displacement solution is obtained even if the void is ignored. The sub-modeling analysis technique can be applied to get the stresses at the void boundary using saint Venant's principle [8].
First, the structure is analyzed without any void. The displacement result is shown in fig.9 and maximum principal stress plot is shown in fig. 4.1.

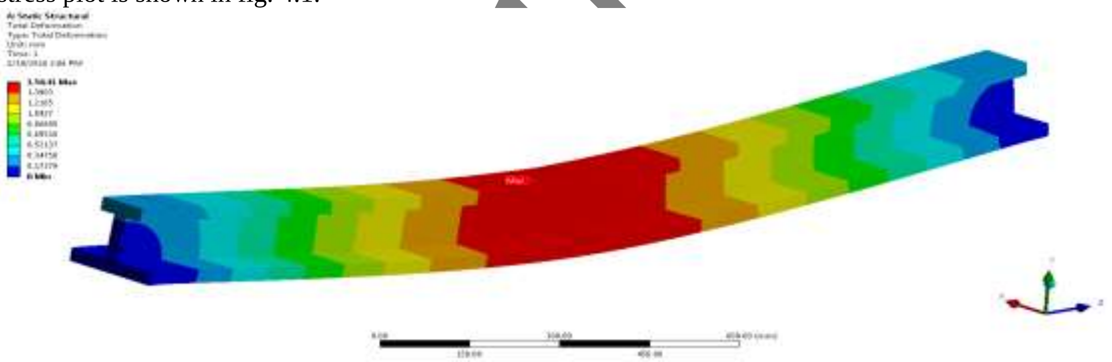

Fig. 4.1 Deflection Without Void

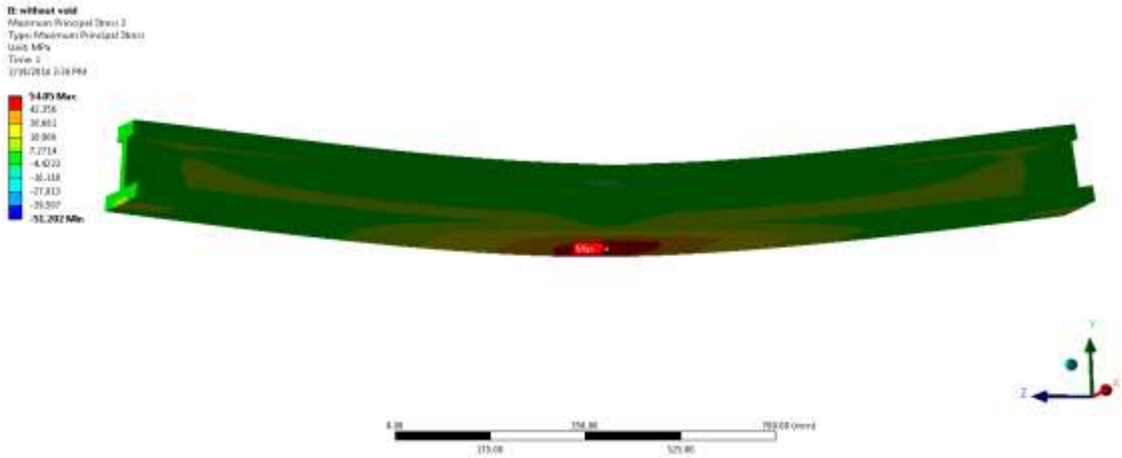

Fig. 4.2 Maximum Principal Stress Without Void

Next, the displacement results are mapped on to the walls of a small parallelepiped containing the void. Then the little sub-modeled structure is then analyzed to get the stresses near the void.

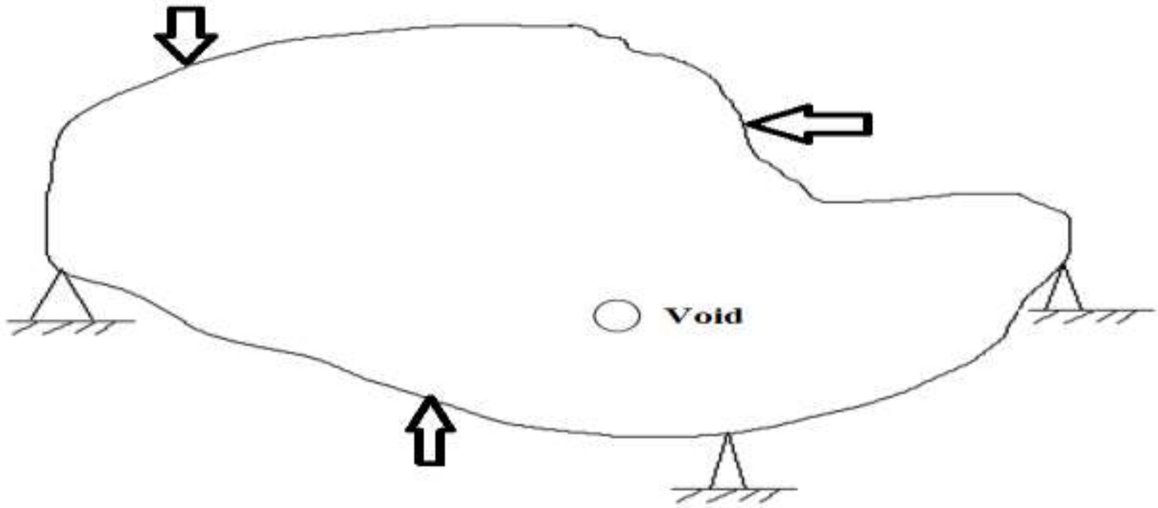

Fig. 4.3 A General Structure with a Void Subject to Arbitrary Boundary Conditions and Loads

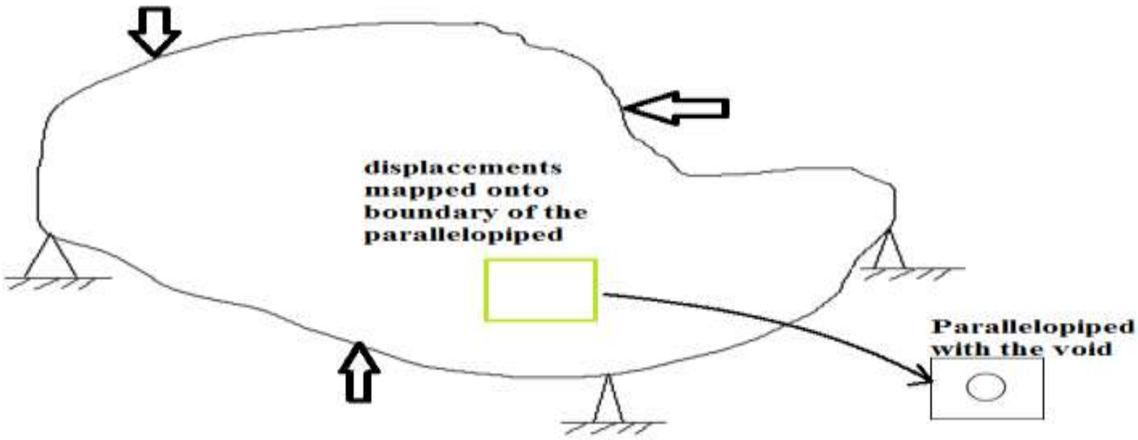

Fig. 4.4 Submodeling Scheme

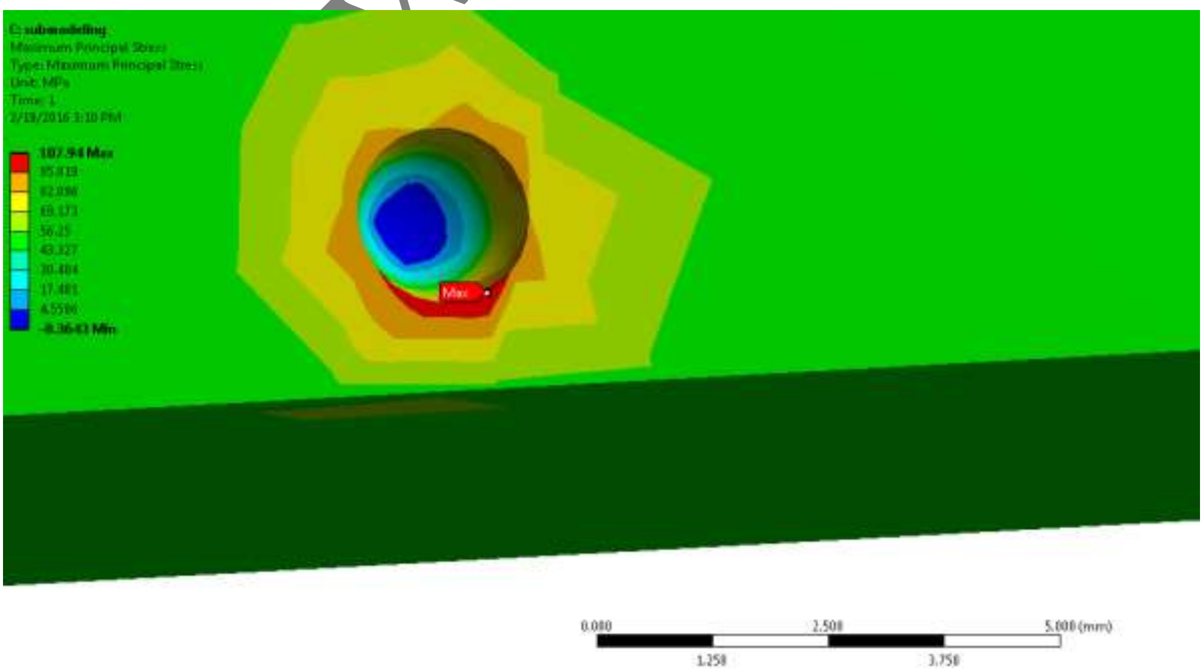

Fig. 4.5 Maximum Stress in the Submodel

5. COMPARISON OF COMPUTATIONAL EXPENSES OF THE ORIGINAL MODEL AND SUBMODEL

The run time of a simulation is proportional to the square of number of degrees of freedom in the model [7]
N1 = No of Degrees of freedom of the original model = 6500163
N2 = no. of degrees of freedom of the model with out void = 746502
Ns = no of degrees of freedom of submodel

= Percentage reduction in simulation time due to submodeling = $\frac{N1^2}{N2^2 + Ns^2} * 100$
= 762%
The total time is reduced by 7.62 times!
The comparative plot of the run times for the original and new model is shown in fig. 5.1.

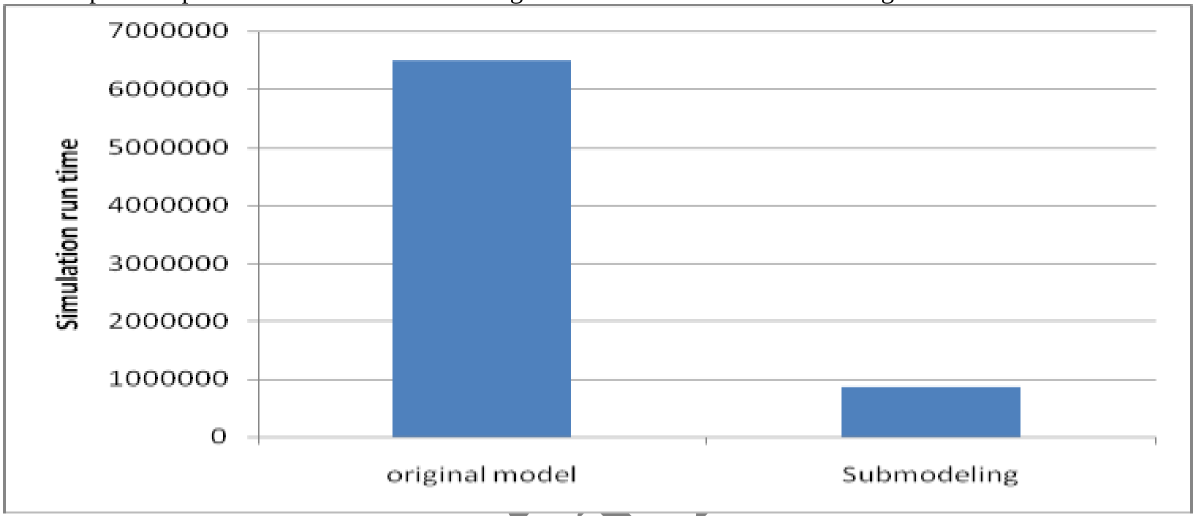

Fig. 5.1 Comparison of Run-Times

CONCLUSIONS

The new innovative technique based on sub-modeling reduces significantly the computational expense and simulation time of the analysis of the cast iron girder in the case study. The method is accurate and efficient and saves significant amount of meshing effort also. In the case study of the cast iron girder, the girder is determined to be safe in spite of the void and also the failure load is found from the fracture mechanics point of view and is found to be more than the stress based value.

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