

Post-Accident Load Carrying Performance of a Deformed Hatch Cover

[Özlem Akkuş, Patrick Kaeding, Ertekin Bayraktarkatal]

Abstract—Evaluation of load carrying performance of damaged structures after accidents is a vital issue for safety concerns. The aim of this study is to investigate the post-accident behaviour of a deformed hatch cover, while comparing the influence of different damage modelling techniques on results and verifying capabilities of an engineering environment for this task. To achieve that, impact load due to a dropped object is analysed as the realistic damage simulation, then the deformed geometry and the residual stresses are transferred to further analyses to assess the performance of the hatch cover under the applied lateral load. The results are compared to the results of the intact structure and the conventionally damage modelled structure. Finally, this study demonstrates the importance of accurate and realistic damage modelling and it is possible to use a single engineering environment for a practical and accurate post-accident evaluation.

Keywords—dropped object, hatch cover, damage modelling

I. Introduction

An accurate and prompt evaluation of post-accidental residual strength of marine structures has significant benefits in terms of life saving, pollution prevention and reduction of repair costs. Thus, residual strength of ships after accidental cases has been among the widely discussed topics in recent years. While the topic is crucial for the overall structure, particularly the importance of hatch covers attracted considerable attention after the loss of M/V Derbyshire with 44 people on board in 1980 during the typhoon Orchid, since one of the most possible loss scenario was the hatch cover collapse under sea loading [1].

A large number of existing studies in the literature have examined residual strength of damaged steel structures [2-8]. Most common conventional methods to represent the damage within the structure are to model the structure with removed

elements or applying a different slenderness ratio in the area of assumed damage. Paik [2] investigated residual ultimate longitudinal strength due to grounding damage by removing the elements in the impact area, while Witlowska [3] focused on locally damaged panels by modelling dent locations with different slenderness ratio.

However, those conventional damage modelling methods are inadequate, because geometric distortion is not the only factor which influences the residual strength and residual stresses due to the plastic deformation should be also considered [4]. For this purpose, Smith and Dow [4] proposed 2-staged method which simulates first the damage by applying and removing lateral load in order to obtain residual stresses and secondly applies axial compressive load to analyse ultimate strength.

Likewise, Nikolov [5] obtained residual stresses through simulation of damage by loading and unloading the plate with forced lateral displacements. In the second stage of the same study, compressive load was applied to the deformed structure and ultimate strength was calculated. Although, this method is more extensive for considering the influence of residual stresses, damage simulation is too rough to represent the real accidental cases. On the other hand, Cai et. al. [6] simulated accident by conducting an impact analysis of a stiffened panel, imported the deformed structure together with the residual stresses to the static stage and applied uniaxial load to assess the residual strength. In both of the studies [5,6], different boundary conditions were defined in damage simulation and compressive loading stages. This leads to inconsistency within the simulation environment. Moreover, transfer methods of the damaged structure to the second stage are not clearly presented.

Although previous studies focused on the residual strength of the damaged structure under the effect of in-plane loads, this load case is not valid for the pontoon hatch covers which are mainly subjected to lateral loads. To the knowledge of authors, no prior studies have investigated the post-accidental lateral load carrying performance of a damaged hatch cover by taking residual stresses into account. Besides, simulation of the damage occurrence accurately and assess the residual capacity might be complicated and computationally time consuming. Therefore, this paper aims to examine the lateral load carrying performance of a deformed sample hatch cover model and the influence of damage modelling techniques through comparative analyses; while investigating the capabilities of the employed engineering environment for such sophisticated analyses in order to present a practical and accurate post-accident evaluation method.

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II. Methodology

Within the framework of this study, performance 4 models have been analysed under the hatch cover design load, indicated by ICLL-1966 [9]:

- Model_1: Deformed hatch cover, damage modelling via accident simulation with residual stresses
- Model_2: Deformed hatch cover with, collapsed elements are eroded, damage modelling via accident simulation with residual stresses
- Model_3: Deformed hatch cover, damage modelling with conventional methods (removing damage area) without residual stresses
- Model_4: Intact hatch cover, for comparison

For Model_1 and Model_2, in order simulate the whole case of an accident and post-accident performance evaluation, a chain of analyses is conducted in the selected software Ansys Workbench. First of all, the damage is simulated, considering that the hatch cover structure is exposed to impact load by a dropped object, which is one of the most common accidental cases for marine structures [10]. Since dropped object case constitutes a highly time-dependent impact load, Explicit Dynamic Analysis System is employed for the solution.

After the explicit dynamic analysis for the damage simulation, the deformed geometry of the hatch cover is exported to further analysis systems and the stress results are transferred as pre-stress. A non-linear analysis is conducted to assess the structural performance of the damaged hatch cover under the design load. While all elements are kept in the deformation area of Model_1, in Model_2, element erosion due to collapse is activated in the analysis system, to obtain a more realistic damage form. This feature enables element removal when the measure of local element distortion exceeds the limit value, in this case failure strain (ϵ_f).

Model_3 is generated by using conventional damage modelling technique which is based on idealisation of the damage by deleting the assumed damage area and excluding from the calculation, without any accident simulation and consequently without having residual stresses. In this paper, the plate on which the rigid object falls, is deleted in a rectangular form while the surrounding stiffeners and girders remain.

Model_4 is the intact hatch cover model without any deformation or stress, to be able to compare and evaluate the performance of damaged models.

Fig. 1 illustrates the workflow which is adopted in this study to achieve the task. The geometric properties of the models are explained in the following sections.

III. Validation of the Method

For the validation of the method which is presented in this paper for the dropped object case, experimental and numerical study of Kim et. al. [11] is considered to be the proper reference.

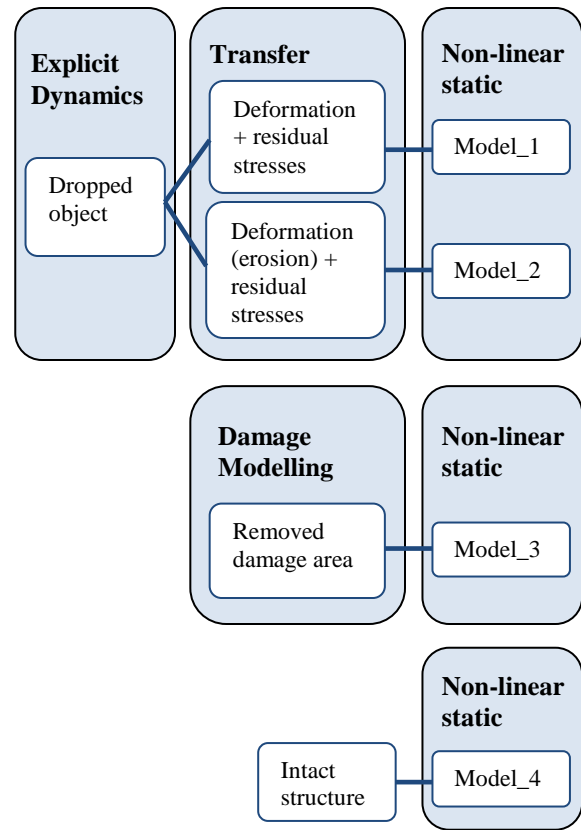


Figure 1. Methodology

Based on the provided data by the authors the Test Model_1 [11] is generated in Ansys Workbench Geometry Modeller. The model consists of a jig which holds the steel plate 1200 x 1200 x 6 mm and a striker whose weight is 11.5 kN.

3803 solid elements with minimum edge length 40 mm are used for the jig, while the steel plate is formed by 3600 shell elements with 20 mm element size. The Ansys model is presented in Fig. 2.

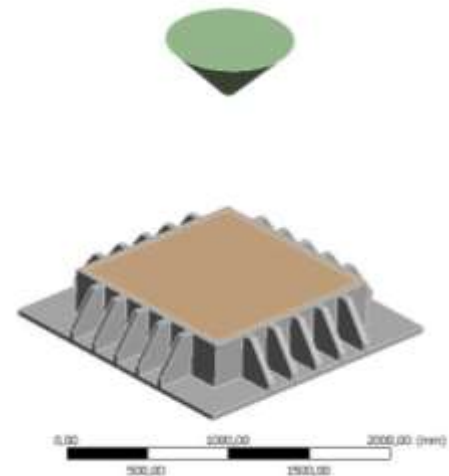


Figure 2. Validation analysis setup

According to the experiment set up, the steel plate is welded to the jig and the striker falls onto the plate from 3 m height. The simulation is conducted with the same boundary conditions, material model Cowper-Symonds with the coefficients $C=3200$, $q=5$ and the analysis setting as described by Kim et al [11] for The Model Type 1 in room temperature.

The deformation result of the steel plate which is illustrated in Fig.3 is compared with the experimental results in Table 1. Fig. 4 shows the deformation results of experiment and analysis over time. The time is set as $t_0=0$ (s) for the moment of impact of the striker on the plate. The results of the simulation are in good agreement with the experiment results. As it is indicated also in the study of Kim et al [11], the striker and the jig are generated accurately as much as possible in compliance with the original experiment setup. This apparent modelling limitation explains the insignificant difference between the simulation and experiment results.

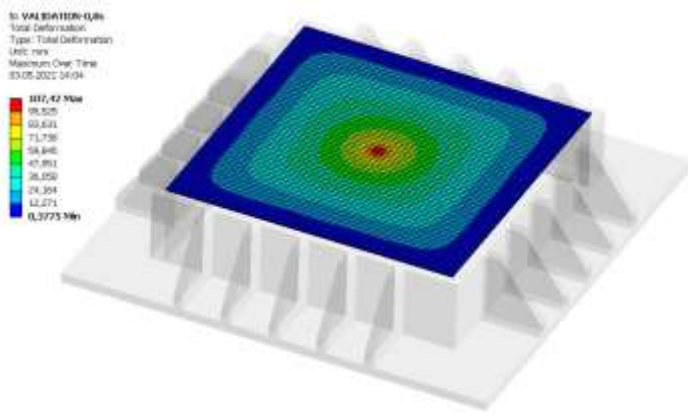


Figure 3. Validation analysis deformation

TABLE I. MAXIMUM DEFORMATION RESULTS

Deformation	Experiment	Ansys Explicit Dyn.
	109.28 mm	107.42 mm

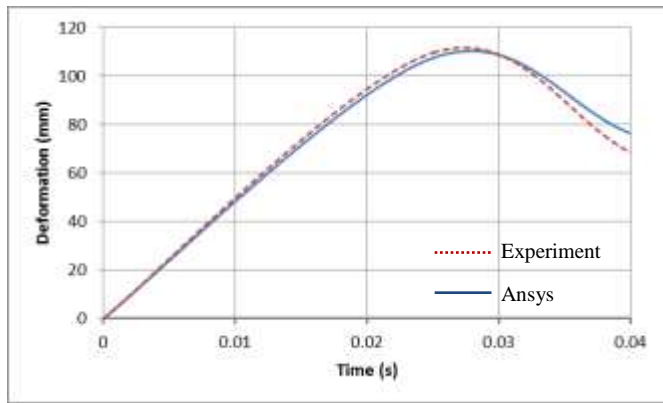


Figure 4. Comparison of Experiment and Ansys Explicit Dynamics Deformation Results

IV. FE Model of the Hatch Cover

A. Geometry

All four models are generated as a part of a hatch cover, based on the model of Akkus and Kaeding [12]. Additionally, the hatch coaming and the adjacent ship structure are integrated for a better representation of the real structure and to evaluate the effect of the impact load on those surrounding structures. The panel length of the hatch cover is 11400 mm, while its breadth is 4750 mm and the thickness is 10 mm. The plate is supported by two longitudinal girders T 800x10x300x10 mm, two transverse webs T 500x10x200x10 mm and nine longitudinal stiffeners L 300x10x125x10 mm. In addition, a hatch coaming plate with 1460 mm height is modelled through the edge of the hatch cover in x-direction. Moreover, another plate which is a representation of a part of the deck with 2000 mm width is attached to the hatch coaming plate perpendicularly on the bottom edge and it is supported by two longitudinal flat bar stiffeners of 200x10 mm. For the simplicity of the modelling and the calculation, the thicknesses of all the plates and stiffeners are assigned as 10mm.

For the damage simulation, a hypothetical 18 t dropped object with dimensions of 1000 x 1000 x 2000 mm which is rotated -45 degree around x-axis is generated. Centre of gravity of the object is positioned at the coordinates $x=2300$, $y=6553.6$, $z=7560$ mm.

B. Mesh and Material Model

The finite element model is generated by assigning SHELL 181 for all structural components of the hatch cover and SOLID 186 for the dropped object. These element types are defined by Ansys Workbench as default for steel and solid structures, respectively [13].

For a lower computation time, the mesh element size is selected as 200 mm which is the highest limit for realistic analysis of failure of materials [14].

High tensile steel is assigned as the material to all structures. The stiffness behaviour of the dropped object is set as rigid. Bilinear plastic material model is defined not only for the simplification of the task, but also for more conservative results that it provides in the lack of reliable data of experiment based material models [12]. Material properties can be seen in Table 2.

TABLE II. MATERIAL PROPERTIES

Material Properties		
Property	Magnitude	Unit
Density	7850	kg/m ³
Young modulus	210	GPa
Poisson's ration	0.3	
Yield strength	355	MPa
Tangent modulus	861	MPa

C. *Contacts and Boundary Conditions*

Between the hatch cover and the hatch coamings on both sides, frictional contact (surface-surface) is defined with the friction coefficient 0.3 [11]. Since a multibody part is formed from the hatch coaming and the adjacent deck structure by joint operation which allows node sharing, another contact definition is not necessary in this region. The same situation is valid for the structural components of the hatch cover.

On the edges of the model in x direction $U_x=U_z=0$ and $rot_x=rot_z=0$ are applied as the boundary conditions to represent the continuity of the structure. The edges in y-direction are fixed by assuming those edges of the deck are welded to the side shell of the ship in reality.

The solid object moves towards to the hatch cover only under the effect of gravity with the acceleration 9.8066 m/s². Fig. 5 shows the boundary conditions of the meshed geometry.

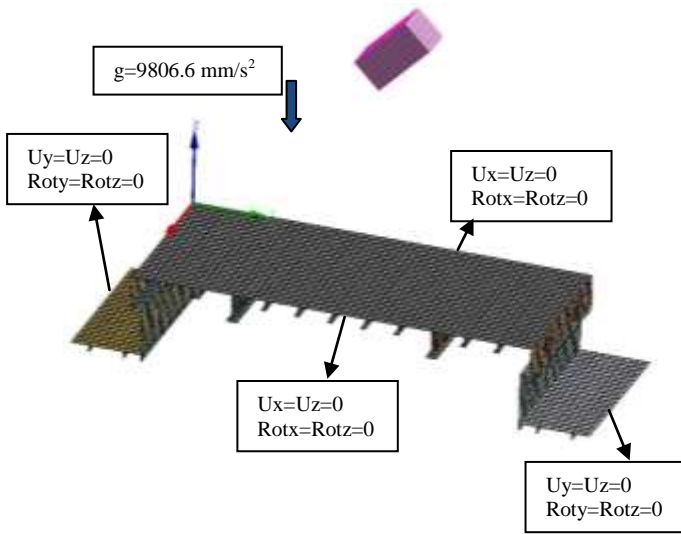


Figure 5. Meshed structure and boundary conditions

V. THE ANALYSES

A. *Damage Simulation - Dropped Object Analysis*

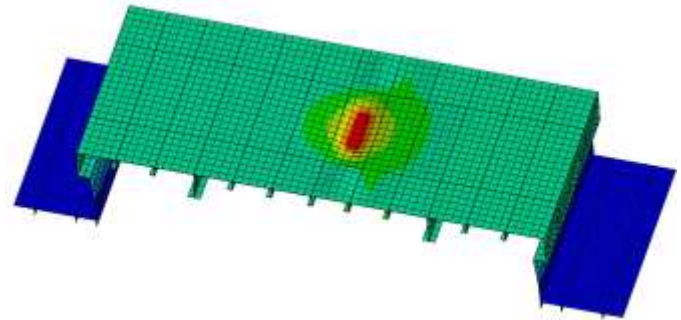
Two separate explicit dynamic analysis systems are utilised to conduct the damage simulation with the settings described above. While in the first analysis for the Model_1 all elements are kept; in the second analysis for the Model_2, element erosion is allowed for the failed elements. Plastic strain value is the main parameter for the structural failure in calculations beyond the elastic range. In this paper, the mesh size based strain failure criteria [14] is used for the failure assessment, in agreement with previous impact studies [check]. Failure strain value is calculated and assigned in the analysis as 0.0830 through the Equation (1). Thus, elements which exceed the failure strain value, are deleted automatically by the features of the software.

$$\epsilon_f(l_e) = \epsilon_g + \epsilon_e \frac{t}{l_e} \quad (1)$$

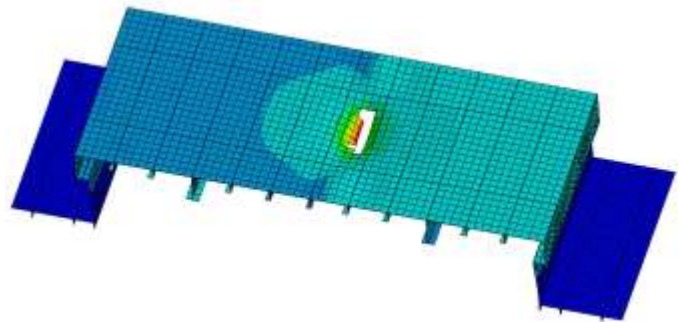
Deformation, equivalent stress and equivalent plastic strain results are presented in Table 3 for Model_1 and Model_2. Fig. 6 presents the deformation results of those two models.

TABLE III. DAMAGE SIMULATION RESULTS

Results	Models	
	Model_1	Model_2
Deformation (mm)	329.98	488.91
Eqv. Stress (MPa)	341.95	310.44
Eqv. Plastic Strain	0.8887	0.07599



(a) Model_1 Deformation



(b) Model_2 Deformation

Figure 6. Meshed structure and boundary conditions

B. *Transfer of the Deformed Structure and Residual Stresses*

One of the objectives of this study is to present a realistic and practical way for post-accident structural evaluations and investigate the capabilities of the employed engineering environment for this purpose. To achieve this aim, the capabilities of the software Ansys 2020 R2 are utilised. The software enables the transfer of the deformed structure into second analysis system by linking the tabs as seen in Fig.4. The deformed geometry is exported from the solution tab of the Explicit Dynamics to the model tab of Static Structural system, based on the deformation results. Residual stresses are transferred as normal and shear elemental stresses for top,

middle and bottom faces of shell elements separately via External Data system. Thereby, residual stress results are read, normal and shear stresses are combined to obtain equivalent stress and defined as “Initial Stress” in the static analysis system.

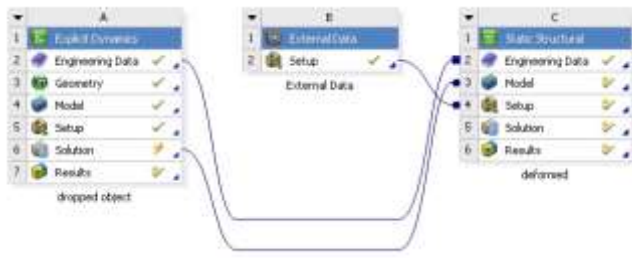


Figure 7. Transfer of the results

VI. Post-accident Performance Evaluation

The load carrying performance of the hatch cover models is investigated by applying lateral pressure, since main structural function of a hatch cover is to withstand green water load which imposes laterally. To determine accurate load cases and to develop more effective methods for safer hatch cover design, several studies have been conducted. After ICLL 1966 [9], in 1997, International Association of Classification Societies (IACS), put UR S21 [15] into effect, which concerns the evaluation of design loads, scantlings of hatch covers and hatch coamings [16].

Since a non-specific hatch cover model is analysed in this paper, for the sake of simplicity, ICLL 1966 [9] design load 1.75 t/m^2 a for hatch covers at a quarter lengths from the forward perpendicular (0.25 L) is applied as a uniform pressure on the top of the hatch cover surface.

Mesh and boundary conditions are kept the same as in the damage simulation for consistency and realistic representation of the whole event chain, in all analyses. Four separate non-linear static analyses are conducted for the evaluation and comparison.

VII. RESULTS AND DISCUSSIONS

For the comparative study, behaviours of the four hatch cover models are analysed through the explained methodology above. Deformation, stress and equivalent plastic strain results of the hatch cover plate are presented in Table 4 and illustrated in Fig. 8, Fig. 9 and Fig. 10 respectively.

Obtained values indicate that the results of conventional damage modelling (Model_3) and intact structure (Model_4) are very close. This implies that the conventionally modelled damage, without realistic damage simulation and disregarding the effect of residual stresses, does not lead to reliable load carrying performance assessment under lateral pressure.

TABLE IV. LOAD CARRYING PERFORMANCE RESULTS

Results	Models			
	Model_1	Model_2	Model_3	Model_4
Deformation (mm)	4.3818	7.2747	4.7888	4.2470
Eqv. Stress (MPa)	277.22	302.33	51.277	51.466
Eqv. Elastic Strain	0.00079	0.00173	0.00025	0.00025
Eqv. Plastic Strain	0.00013	0	0	0

On the other hand, Model_1 and Model_2, which are generated by damage simulation, give more realistic results. However, Model_1 remains more conservative than Model_2, since the failed elements are kept as a part of the structure in the further analysis.

Furthermore, in Model_2, the failed elements of the deformed structure are eroded, therefore strain values remained in the elastic range in the static analysis in which stress results do not exceed the yield strength 355 MPa for high tensile steel. In contrary, plastic strain values are obtained for Model_1 in the static stage, due to preserved elements with high stress and strain values from the damage simulation.

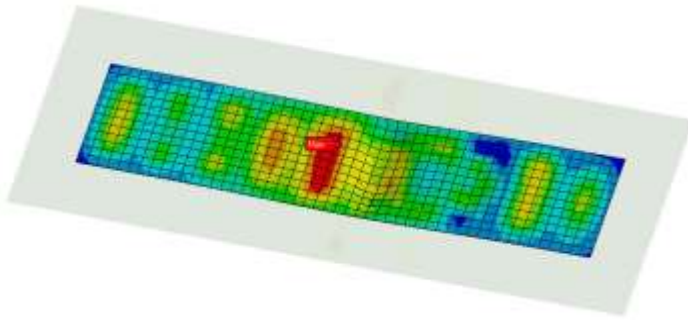
VIII. CONCLUSION

Within this paper, post-accident performance of a hatch cover sample is investigated by employing capabilities of an engineering environment to execute an accurate, practical and prompt calculation. In addition, influence of damage modelling techniques on results are observed and compared.

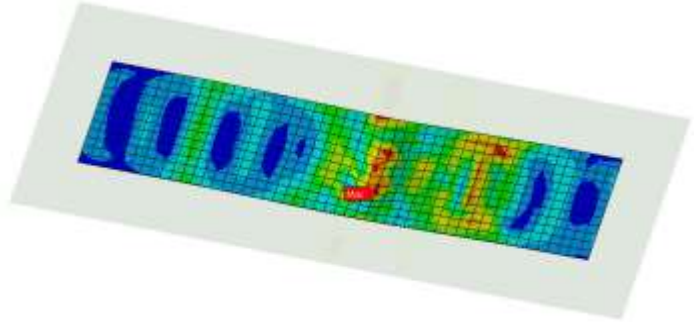
The validation of the method and the analyses of the hatch cover ensure that the proposed method and the engineering environment are capable enough for the assessment of the structural performance of structures after impact damage. The combination of impact and static analyses forms a base, to use integrated engineering environments for sophisticated analyses of load carrying capacities.

Comparative studies confirm that damage modelling is an important factor for post-accident structural evaluations. Conventional methods, as removing the assumedly deformed area without residual stresses, are not sufficient enough for realistic assessment. Thus, it is critical to simulate the accidental case properly and to use the accurate deformation and residual stress data in further analyses.

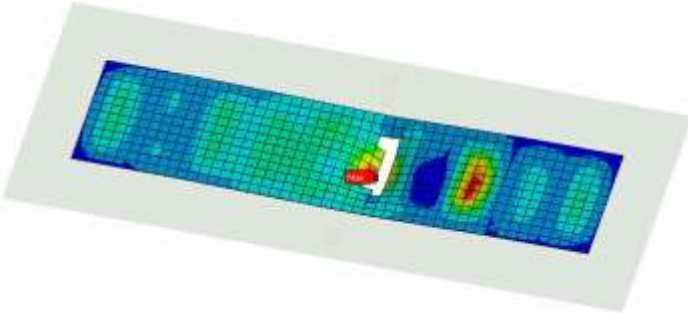
The present study investigates post-accident behaviour only under the design load; consequently it is recommended to focus on determination of the collapse load for deformed hatch cover in future works.



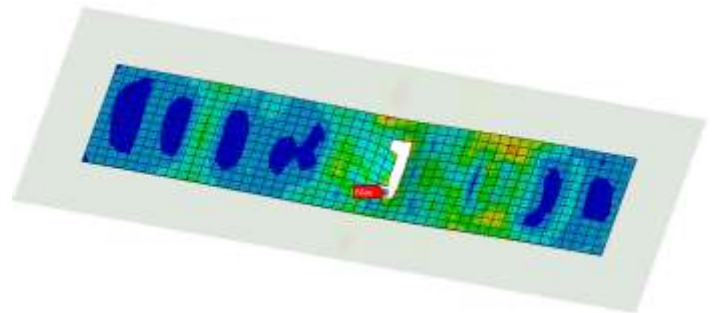
(a) Model_1 Deformation



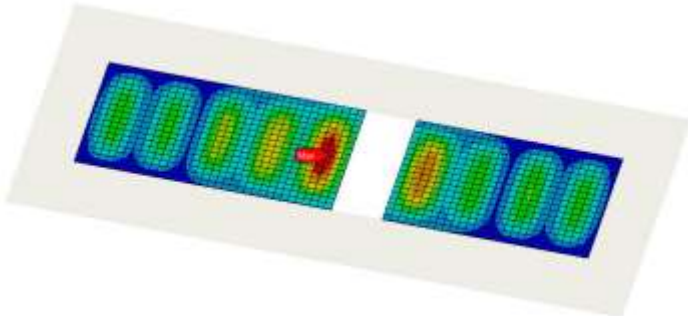
(a) Model_1 Equivalent Stress



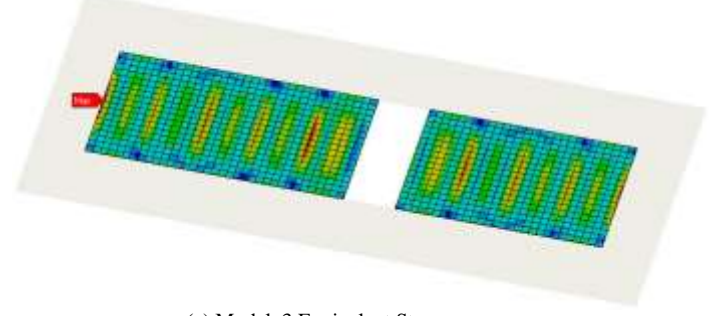
(b) Model_2 Deformation



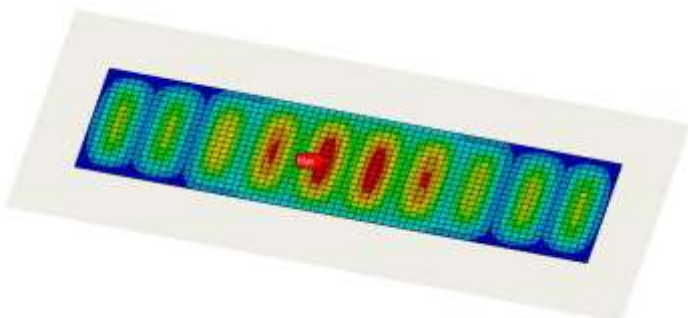
(b) Model_2 Equivalent Stress



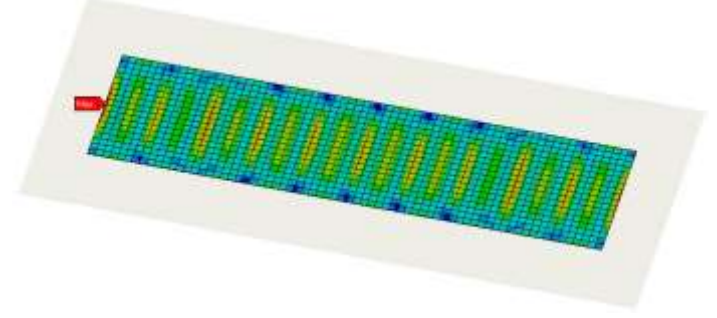
(c) Model_3 Deformation



(c) Model_3 Equivalent Stress



(d) Model_4 Deformation



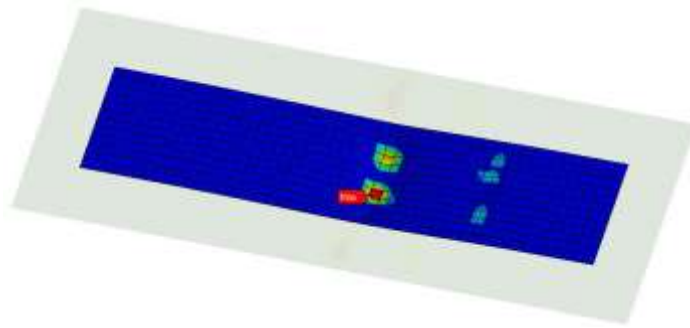
(d) Model_4 Equivalent Stress

Figure 8. Deformation results of load carrying evaluation

Figure 9. Equivalent stress results of load carrying evaluation

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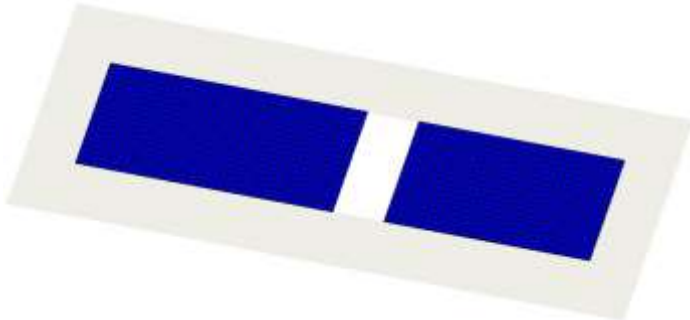
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(a) Model_1 Equivalent plastic strain



(b) Model_2 Equivalent plastic strain



(c) Model_3 Equivalent plastic strain



(d) Model_4 Equivalent plastic strain

Figure 10. Equivalent plastic strain results of load carrying evaluation