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Introduction and application of multi-point constraints method for connecting shell to solid element in Finite Element Analysis

Mostafa Omidi Bidgoli [1]

1 Assistant Professor of School of Mechanical Engineering College of Engineering Islamic Azad University, Badroud branch

mostafaomidibidgoli@gmail.com

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Abstract: One of the most widely used numerical methods in engineering problems is the finite element technique. So far, various finite element formulations have been proposed and implemented in FE software packages. Connecting elements and nodes to the adjacent elements play a critical role in defining the movement constraints and the transition of stress field within the FE model. In many applications, surface elements are required to be accurately joined to the neighboring solid elements. In this article, the shell-to-solid coupling technique is introduced and its reliability is evaluated via FE simulations and real experiments. Results revealed a good agreement between that simulation and experimental results

Keywords: nanotube, vibrations, Eringen nonlocal theory, stability

1. Introduction

The finite element (FE) method is a powerful numerical method for analyzing engineering problems. In this method, each continuous field variable such as velocity, stress, pressure or temperature is approximated by a separate model consisting of a set of continuous field variables. In a finite element model, the area of interest is divided into discrete shapes called elements. Then, filed's variables such as displacement are directly calculated in each node of the element and approximated throughout the element using shape functions. During the calculation process, nodal constraints should be considered for adjacent elements. In this regard, connecting surface elements to volume elements plays an important role in the accuracy of the approximations [1, 2]. A number of coupling formulations such as Mixed-dimensional technique [3-5], shell to solid coupling method [6-12], and kinematic coupling [13] have been used for various mechanical simulations. Wang et al.[14] evaluated the performances of elastic-plastic buckling and shell-solid coupling in finite element analysis on plated structures with and without corrosion defects. Yamamoto et al. [15] presented a numerical procedure to couple shell to solid elements by using Nitsche's method. Omidi bidgoli et al.[16] performed a structural analysis on the oil storage tanks with crack and pitting corrosion using shell to solid coupling technique. In the present study, due to the widespread application of the shell-to-solid coupling technique, its principles are introduced and the accuracy of the mentioned technique is evaluated using experiments.

2. Theory of shell-to-solid coupling method

The connection of surface and volume elements is usually done by multi-point constraints [17]. This technique provides an smooth transition of stress fields between adjacent elements with the minimum fields' distributions, making it suitable for geometrically nonlinear analyses [18] nonlinear materials such as plastic, non-isotropic and composite elastic materials [3, 4, 19] and nonlinear loading conditions such as fatigue analyses [7]. As the name implies, the implementation of shell to solid coupling method includes imposing constraints on certain multi-point at the interface [2] aiming at providing the continuity and integrity of the solid-shell connections. Figure 1 illustrates examples of shell-solid couplings in typical finite element models.

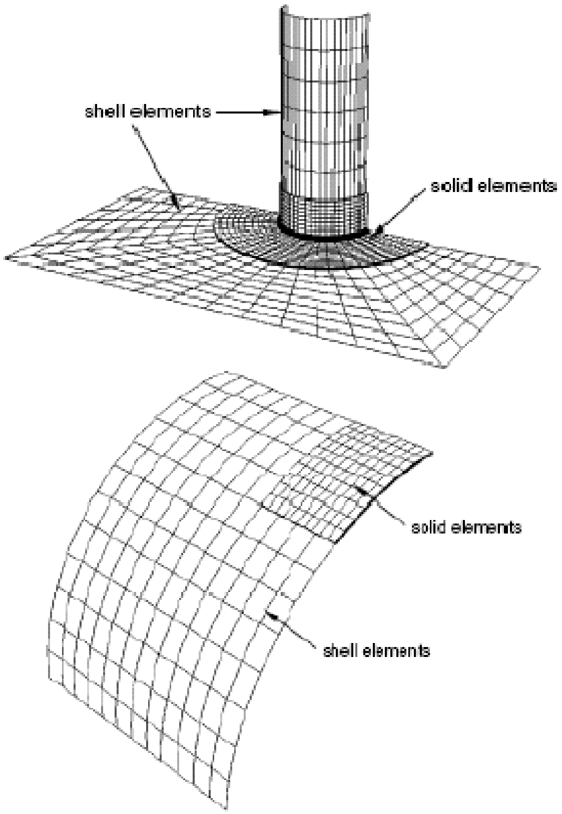
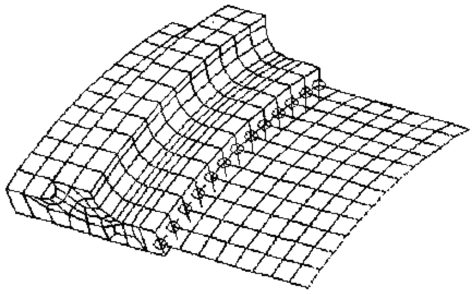


Fig. 1 Examples of connecting a shell to solid element [2]

Multi-point constraints are used to connect surface elements to volume elements. Despite volume elements that have only three degrees of translational freedom, surface elements have an extra degree of rotational freedom. The multipoint constraint equations creates a relationship between the nodes of the surface elements and the corresponding nodes on the upper and lower edges of the adjacent volume elements. According to the Figure 2, this relationship can be expressed as Eq.(1). The displacement of the surface elements in a cylindrical system (z,r,θ directions) can be expressed in terms of the displacement of the existing nodes on the lower and upper edges of the volume elements [2].



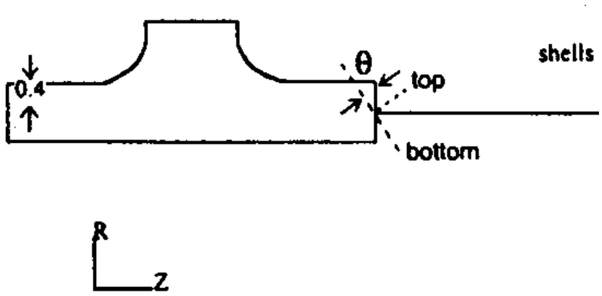


Fig. 2 An example of a multi-point constraint in a structure [2]

$$u_r^{shell} = 0.5\,(u_r^{top} - u_r^{bottom}) \qquad (1)$$

$$u_\theta^{shell} = 0.5\,(u_\theta^{top} - u_\theta^{bottom})$$

$$u_z^{shell} = 0.5\,(u_z^{top} - u_z^{bottom})$$

In the above equations, the displacement of the surface element nodes at the junction with the volume element is expressed in terms of the displacement of the upper and lower nodes. To evaluate the rotation of the surface element, assume that the surface always remains perpendicular to the adjacent volume elements. If θ is too small, $\sin\theta = \theta$. Thus:

$$u_{rotR}^{shell} = 0 \qquad (2)$$

$$u_{rot\theta}^{shell} = 0.25\,(u_z^{top} - u_z^{bottom})$$

$$u_{rotz}^{shell} = 0.25\,(u_\theta^{bottom} - u_\theta^{top})$$

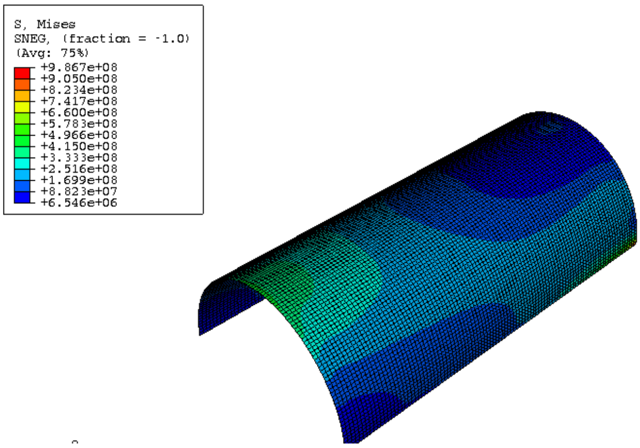
In Eq.(2), the angular positions of the shell element' nodes at the junction with the solid element(R_Z, R_θ, R_r) are expressed in terms of the displacement of the upper and lower nodes of the volume element.

3. Results and discussion

COMPARISON BETWEEN THE SHELL MODEL AND COMBINED SHELL-SOLID MODEL

To evaluate the accuracy of the method, two similar FE models were analyzed. The first FE model consists of only shell elements but the second model includes some volume elements constrained with shell-to-solid coupling algorithm. ABAQUS V6.6.1 software was used for FE simulations. S4R and C3D8R elements were assigned for shell and solid structures, respectively. Mesh convergence analysis was then performed to determine the optimal number of elements and based on the obtained results, FE models were created with 10,000 elements. Figure 3, depicts the von mises stress contour obtained for each model.

(a)



(b)

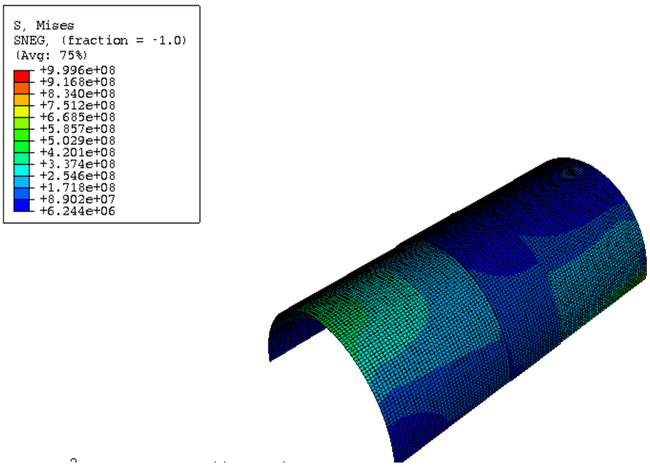


Fig. 3 Von Mises stress distribution in a cylindrical model consisting of (a) shell and (b) shell-volume elements

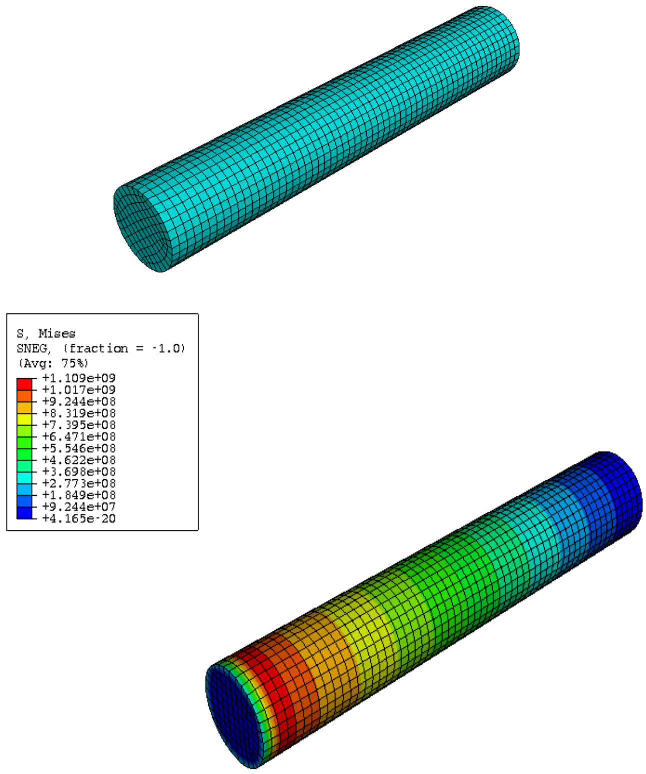
The maximum Von-mises stress in the first and the second models were 986.7 and 999.6 MPa, respectively, showing a 1.3% difference in the obtained results.

Case study: hydrostatic test of cylindrical pressure vessels

In the present study, hydrostatic pressure test of a pressure vessel was studied via the FE simulation and the shell-to-solid coupling technique. The hydrostatic pressure test is conducted to determine the failure pressure and critical length of the cracks in faulty reservoirs. To ensure the reliability of the developed FE model, simulation results were compared to the results of the destructive hydrostatic experiments. The applied pressure as well as the stress level are critical parameters in each stage of deformation that should be measured accurately. Considering the destructive nature of the mentioned test, developing a reliable and accurate FE model, considerably reduces the time and expenses of real experiments. The Center for Non-Destructive Testing Information Analysis in the United States tested a number of high-pressure aluminum and steel cylinders under hydrostatic pressure during a regular program [20]. To determine the failure pressure and critical dimensions of the crack, some cylinders with a series of initial longitudinal cracks on their outer surfaces were uniformly pressurized up to the failure point. The inner diameter, height, and the yield strength of the tested cylinders were 222mm, 1295mm, and 972-1111 MPa, respectively. To assess the accuracy of the shell-to-solid coupling technique, FE models of the pressurized cylinders were created using shell (S4R) and solid (C3D8R) elements in ABAQUS software. Figure 4 illustrates the FE models and the stress distribution within the modeled cylinders.

Table 1 presents the results obtained by the experiments and FE simulations. As the Table 1 shows, the prediction of the failure pressure by the implemented FE method deviates 6 and 3.5% from the results obtained by the experiments for the crack-free and faulty cylinders, respectively, showing a good agreement between the simulation and experimental results.

(a)



(b)

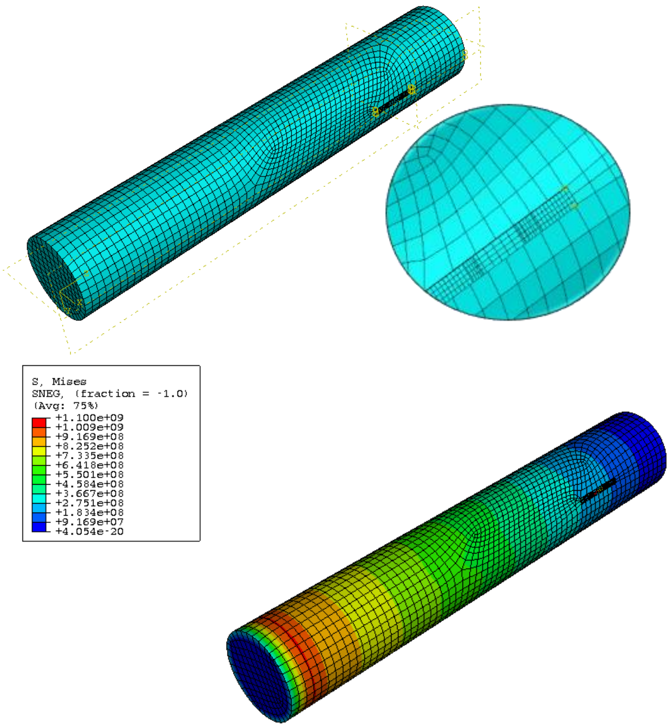


Fig. 4- Finite element model and Von-Mises stress distribution for (a) crack-free and (b) faulty cylinders

Table 1- Comparison between the results of the hydrostatic pressure test on cylindrical reservoirs with initial cracks and FE simulations

model number	Type of defect	Wall thickness (mm)	Crack length (mm)	Crack depth (mm)	Failure Pressure (MPa)	
					Experiment [20]	FE simulation
1	Without defect	6.299	-	-	69.29	69.29
2	Crack	6.833	68.326	3.302	57.22	57.22

4. Conclusion

The reliability and accuracy of the shell-to-solid coupling technique in ABAQUS software was evaluated in the present study. The results showed the accuracy of the technique is relatively high compared to the case where the whole model is modeled and analyzed as a surface. The studied FE method is simple and straightforward and can be widely used in fatigue and crack's propagation analyses.

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