A Hybrid Finite Element Model of a Missile Launcher Frame

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Abstract: In the course of war or actual combat, military vehicles and warships are indispensable military forces, whose structural performance are critical for combat performance. For this sake, in the design phase, a large number of numerical simulations are usually needed to guide the optimization design. Generally, the finite element model uses shell element and solid element to obtain more accurate results, but this greatly lengthened the computational cycle, which seriously reduces the design efficiency. In order to solve this problem, a hybrid model for the shipborne launcher frame is proposed in this paper. Its accuracy and efficiency were verified by comparing with the other two kinds of finite element models. The results show that the proposed hybrid model provides a good balance between computational efficiency and accuracy for model and stiffness analyses of truss-like structures such as the launcher frame.

1. Introduction

The missile launcher is a specific device for loading missiles and other equipment on military vehicles and warships, located in the launch module. The mechanical properties of the launcher frame directly affect the stability and safety of the vehicle and the warship, especially during the missile launching process. In this regards, we often use numerical simulations to obtain the mechanical behaviours of the launcher frame for time saving and fast design iteration.

The launcher frame is mainly composed of steel pipes. In finite element (FE) models, beam elements and shell elements are generally used to model such frame. In this work, a hybrid model is proposed combining the computational efficiency of the beam element model and the accuracy of the shell element model. Both FE modelling and simulations were carried out in Altair HYPERWORKS® 14.0.

2. Finite Element Models of Missile Launcher Frame

2.1. Shell Element Model

In numerical simulation, the shell element model can reflect the complete geometric features, local stress and other more detailed mechanical behaviours of the structure. Meanwhile, the computational efficiency of the shell element model is higher than that of the solid element while ensuring high accuracy [1]. In order to make a better stress analysis in the thickness direction, the shell element model was first built for the launcher frame, as shown in Figure 1a. In this work, the shell element model is assumed to be accurate and used as a standard model for evaluation of the other two.

2.2. Beam Element Model

In reality, there are often complicated models with many components. In case of evaluating overall structural performance while neglecting local stress distribution, using beam element model will save a lot of computational time and improve the design efficiency [2]. To analyse and compare

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the performance of different FE models of the launcher frame, as well as to evaluate the reliability of the hybrid model, the beam element model was established, as shown in Figure 1b.

2.3. Hybrid Model

Usually, in beam element model, joint is simplified as a completely rigid node with greatly reduced accuracy [3]. In order to improve the computational efficiency while ensuring the accuracy, it is necessary to simplify the FE model rationally. For the launcher, the key is to achieve the equivalent FE model of joints. According to the literature, joint equivalent modeling methods can be roughly divided into two categories [4] ~ [6]:

1) Equivalent connection modelling method. Using beam elements combined with shell elements or solid elements, and connecting them in a more rigorous way, and finally obtaining a model mainly composed of beam element and the joints are modelled with shell or solid elements.

The methods to achieve equivalent connection mainly include: a) MPC method, the equivalent connection is realized by coupling the nodes' degrees of freedom, i.e., the degree of freedom of a certain node is used as standard, and the relationship between other nodes' degree of freedom and this standard value is specified. The general MPC formula is as follows:

$$U_i + \sum C_j U_j = C_0 \quad (1)$$

where U_i and U_j are degrees of freedom of dependent and independent nodes respectively; C_j is the weight coefficient; C_0 is a constant; i, j are the subscripts of the dependent and independent nodes' degree of freedom. The method does not require geometric position correspondence of nodes at junction, and can be used to connect discontinuous, uncoordinated element by internally generating a constraint between multiple nodes. Therefore, the workload is small. b) Superelement method, through the Guyan or Kuhar reduction method, retaining independent nodes' degree of freedom while omitting dependent nodes' degree of freedom, superelements can be established to connect joints and beam element nodes.

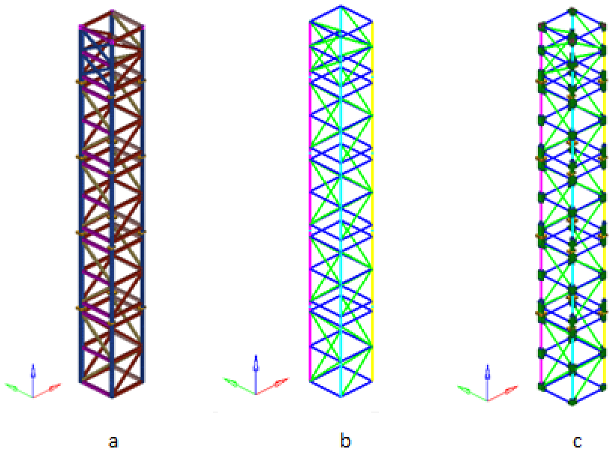

Figure 1 a) shell element model b) beam element model c) hybrid model.

2) Equivalent substitution method: by calculating the flexibility of the actual joint, the section property and moment of inertia of the virtual or equivalent unit are equivalently obtained and the hybrid model whose overall structure is beam element can be built. The virtual or equivalent unit models include: a) beam-spring element model; b) equivalent beam unit model.

Since the launcher frame joints are mostly composed of more than three beams, it is difficult to use the equivalent substitution method because the process to acquire the joint flexibility is complicated. Therefore, equivalent connection modelling method is adopted in this work. The hybrid model of the launcher frame includes mainly beam element, and the joints are modelled with shell element. MPC connection method is used, taking the node at the end point of the beam as independent node and the shell element node as dependent node, as shown in Figure 1c.

3. Comparison of Different Models

3.1. Modal Analysis

Modal analysis is an important method for structural dynamic design and fault diagnosis. Designers often take the structural modal frequency into consideration, and make the natural frequency of the structure different from the excitation frequency. Moreover, the component modal frequencies are designed to be different from each other in lest of resonance causing noise and other problems [7]. When warships marching, especially under bad sea conditions, the influence of the excitation frequency such as waves and sea breeze can be a threaten to the warships' safety. The natural frequency of the launcher frame should avoid these frequencies.

The first-order modal shapes of the frame obtained by different models are shown in Figure 2. The first 10 modal frequencies of different models and their relative errors to the shell element model are shown in Table 1. It can be seen from the displacement contours of the launcher frame that the maximum displacement and its distribution are different in different models. The maximum displacements of the shell element model and the hybrid model are in the same position, i.e., the bottom of the launcher frame. As for the beam element model, the amplitude and location of the maximum displacement are different from the shell element model. We can easily find that the first 10 modes of the shell element model and the hybrid model are similar. Furthermore, as the order increases, the difference between eigenfrequencies of the two modal frequencies becomes smaller. The relative error of the hybrid model with respect to the shell element model is between 0.81% and 10.95%, and the average is 5.11%, while the beam element model's relative error is very large, ranging from 10.29% to 69.75%, with an average of 31.42%.

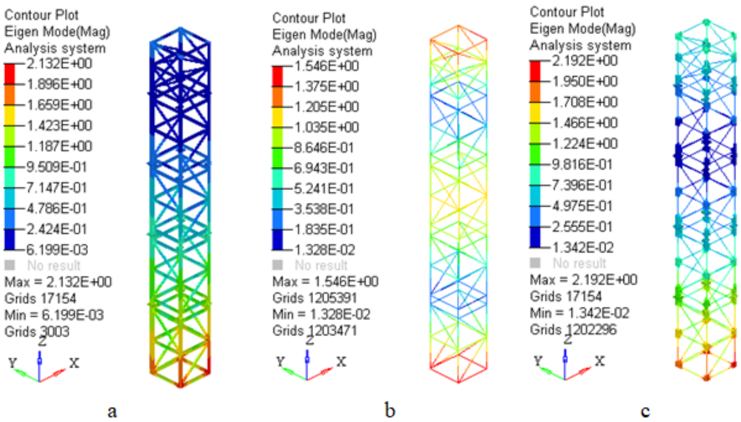

Figure 2 modal analysis result a) shell element model b) beam element model c) equivalent model.

Table 1 modal frequency and tolerance of each model.

Order	Shell element model	Beam element model		Hybrid model	
	Frequency/Hz	Frequency/Hz	Relative error	Frequency/ Hz	Relative error
1	36.79	43.91	19.35%	32.93	-10.49%
2	37.36	44.42	18.90%	33.27	-10.95%
3	38.82	47.80	23.13%	41.12	5.92%
4	40.71	66.16	62.52%	42.03	3.24%
5	41.06	69.70	69.75%	42.67	3.92%
6	52.19	79.67	52.65%	50.71	-2.84%
7	73.26	86.13	17.57%	78.36	6.96%
8	79.46	87.64	10.29%	80.10	0.81%
9	82.13	95.01	15.68%	85.34	3.91%
10	88.13	109.58	24.34%	89.98	2.10%

3.2. Stiffness Analysis

The displacement method is often used in structural stiffness analysis to obtain the deformation and stress of the structure under certain loads. Stiffness is the ability of components to resist elastic deformation under load. The stiffness of a part is usually expressed by the force or torque required for unit deformation. Stiffness depends on structure and material [8].

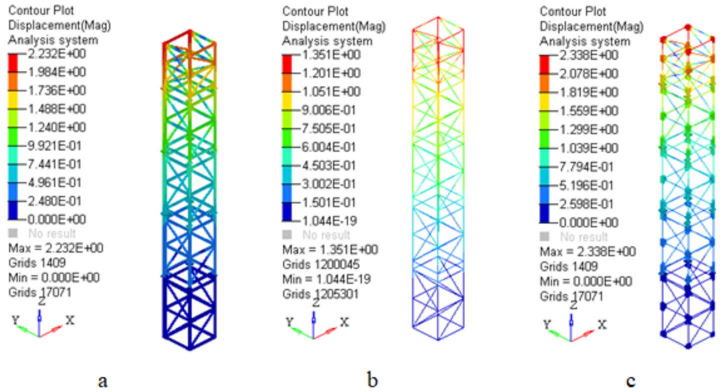

Figure 3 Displacement contours under torsion: a) shell element model b) beam element model c) hybrid model.

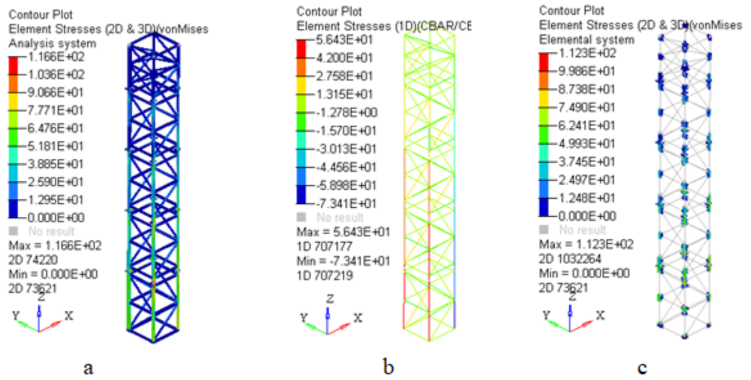

Figure 4 Stress contours under bending: a) shell element model b) beam element model c) hybrid model.

Table 2 result of each model under two different conditions.

Model type	Torsional loading condition				Bending loading condition			
	Max deformation/ mm	Relative error	Max stress/ MPa	Relative error	Max deformation/ mm	Relative error	Max stress/ MPa	Relative error
Shell element model	2.23	-	86.69	-	24.16	-	116.6	-
Beam element model	1.35	39.46%	8.28	90.45%	20.78	13.99%	56.43	51.60%
Hybrid model	2.34	4.93%	95.52	8.83%	22.81	5.59%	112.3	3.69%

When launching a missile, the launcher frame is subjected to a certain load which demands the frame stiffness meeting the requirements. When analysing the stiffness of the launching frame, the bottom of the frame is fully constrained, and the torsion load around the Z-axis and the bending moment around the Y-axis were exerted at the top of the launching frame for both stiffness analyses. To ensure consistent application of working condition on different models, for the shell element model and the hybrid model, we created RBE3 at the boundaries. Equal loading was applied on the corresponding nodes in different models.

Torsional deformation and bending stress contours of the three models are shown in Figure 3 and Figure 4, respectively. The maximum deformation and stress values under both working conditions predicted by each model are shown in Table 2. It can be seen from the figures and the table that the maximum deformation and stress of the beam element model is very different from the shell element model under both conditions, while that of the hybrid model are close to that of the shell element model. For the hybrid model, the relative error of maximum deformation with respect to the shell element model is within 6%, and the maximum stress within 9%. In contrast, the relative error of the beam element model, the relative errors of maximum deformation and maximum stress are 14% and 90%, respectively.

4. Conclusions

In this paper, three different finite element models are established for a shipborne launcher frame. By comparing and analysing the numerical simulation results, the following conclusions are drawn: 1) the simulation result of the beam element model is very different from that of the shell element model. Due to its completely rigid connection, the structural rigidity is greatly increased, which seriously affects the design. Therefore, for the launcher frame, it is inappropriate to use simplified beam element model directly. 2) In truss structures such as the launching frame, the joint has a great influence on the stiffness of the overall structure. When simplified model is inevitable, an appropriate method of joint equivalent modelling can help to improve the accuracy of the model. 3) The proposed detailed joint-beam element hybrid model of the launcher frame yielded relative errors of modal frequency and stiffness both within 10% with respect to that of the shell element model. The hybrid model features both computational efficiency and the accuracy of the solution, and can be used for FE modelling of truss structures such as the shipborne launcher frame.

Acknowledgements

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