Optimization for Finite Element Model of a Steel Ring Restrainer with Sectional Defect

Qiang Zhang, Yue Ma, Jin Feng, and Zhanfei Wang

Abstract Performances of the steel ring restrainer (SRR) as a typical steel structural component can be impaired due to a presence of initial geometrical defects or metallic corrosion. In this paper, finite element (FE) models of the SRRs with a sectional defect were optimized, and then a convenient and effective method was proposed to establish FE models. By comparing the force–displacement, stress distribution, stress triaxialities and analysis duration, it is found that analytical results of optimized models are good agreement with analytical results of models with solid elements, and meanwhile, optimized models present the higher calculation efficiency. The monotonic loading tests of SRRs were conducted to further verify the effectiveness of the optimized models. The optimized method of the FE model was proposed, and it can provide a reference for the research of related topics. The experimental results also show that the proposed method can obtain accurate analytical results in a relatively short time.

Keywords Finite element model · Steel ring restrainer · Sectional defects

1 Introduction

In current earthquakes, restrainers have shown good restraint effects in both the longitudinal and transverse directions, so that they can effectively reduce occurrences of the bridge unseating [1]. In China, due to the late start of the research on the mechanical performance of the restrainers, the restrainers are just as an attachment. Therefore, it is still necessary to further explore the mechanical performance of the

Q. Zhang (✉) · J. Feng · Z. Wang (✉)
Shenyang Jianzhu University, Shenyang 110168, China
e-mail: zhangqiang@stu.sjzu.edu.cn

Z. Wang
e-mail: ZFWang@sjzu.edu.cn

Y. Ma
Applied Technology College, Dalian Ocean University, Wafangdian 116300, China

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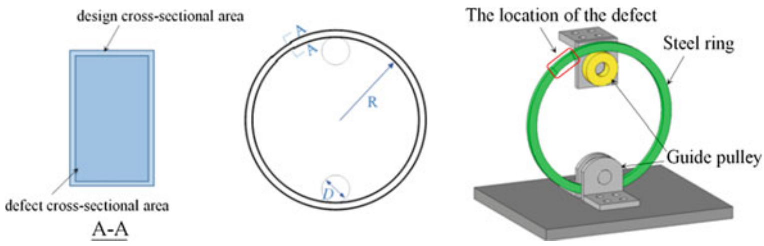
restrainers. Many scholars have studied a lot of research on the mechanical properties of rigid stoppers, cables and SRRs, and their research methods are mainly theoretical calculations, experiments and numerical simulations [2–4].

For structural components of complex configuration and forces reception, theoretical calculations have difficulty to accurately analyze their mechanical properties under various external conditions and design parameters. On the other hand, it requires extremely high-standard test condition to obtain convincing results by tests. As the era of evolution of computer technology, the applicability of finite element analysis software has been improved. Numerical simulation methods can obtain more accurate results, meanwhile consume less manpower and material and have become one of the most commonly used analytical methods by most scientific researchers. The modeling method is chosen to establish the FE model, such as element type, meshing method and model simplification measures, and has a great impact not only on the accuracy of the analytical results, but also on operation costs and calculation time. Therefore, choosing an appropriate modeling method is a critical step.

The previous study showed that the section size of the device is the main factor affecting its restraint ability [3, 4]. The effect of the overall section size was assessed instead of the local section size. Therefore, it is necessary to further study the mechanical properties of the SRR with sectional defects. This paper optimizes the finite element model of the SRR with sectional defects, proposes a method for establishing an optimized FE model with high efficiency and high accuracy and compares it with the experimental results and simulation results of the solid model. The comparison of the results verifies the effectiveness of the optimization model. Researchers and engineers can use this model to obtain more accurate analysis results in a short time.

2 SRRs with Sectional Defects

The sectional defects of the SRR can be divided into two main categories. One of them is the error during processing in the factory or the initial defect of the steel plate, and the other is caused by the influence of the external environment on the device during the engineering application, such as the corrosion in the atmospheric environment and the defect due to impact. The cross-sectional defect rate, which is the ratio of the difference between the defective cross-sectional area and design cross-sectional area to the design cross-sectional area, is often used to describe the degree of defects [5]. In this paper, 15% and 30% are used as the cross-sectional defect rate, and the design cross-sectional area is 120 mm^2. Figure 1 depicts a typical SRR with sectional defects. The R is the radius of the steel ring, and D is the diameter of the guide pulley. In this paper, D and R are 40 mm and 120 mm, respectively. The A-A section represents the cross section of the defect on the steel ring.



(a) A-A section (b) 2-D diagram (c) 3-D diagram

Fig. 1 SRR with sectional defects

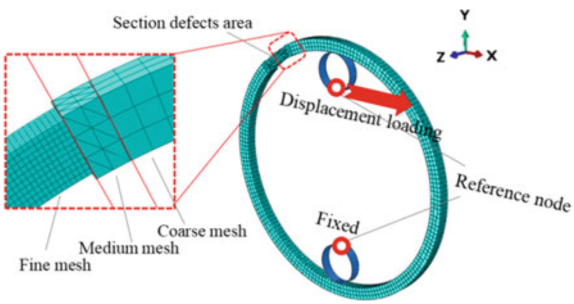
3 Finite Element Model and Optimization Method

3.1 Solid Element

For the numerical simulation of three-dimensional geometric members, choosing 8-node linear brick stress/displacement elements (C3D8R) is intuitive and reliable [6] (Fig. 2).

The C3D8R was selected to model the steel ring, and the guide pulleys were modeled by the analytical rigid body. The degree of freedom in the *x*-axis direction of the upper guide pulley is free, and the unidirectional displacement is employed along the *x*-axis direction. The lower guide wheel adopts fixed constraint. In the sectional defect area, transition area and other areas, the fine mesh, medium mesh and coarse mesh are used, respectively. The steel yield strength, ultimate strength and Young's modulus are 294 MPa, 424 MPa and 216 GPa, respectively.

Fig. 2 C3D8R model



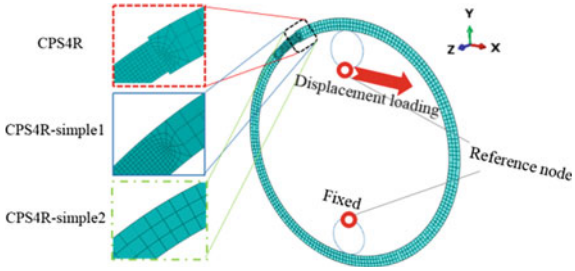


Fig. 3 CPS4R model and two optimization models

3.2 Optimization Models

Combining the previous study, 4-node bilinear plane stress elements (CPS4R) are used to simulation the steel ring with sectional defects. The model is shown in Fig. 3.

In Fig. 3, the CPS4R-simple1 and CPS4R-simple2 are the two optimization models that are mainly compared and analyzed in this paper. The CPS4R model: The steel ring adopts CPS4R. The boundary conditions and loading pattern are the same as the C3D8R model. The method is almost the same as the C3D8R model. The CPS4R-simple1 optimization model: Compared with the CPS4R model, this model ignores defects in section height but applies such defects to the thickness direction based on the same cross-sectional defect rate. The CPS4R-simple2 optimization model: Compared with CPS4R-simple1, a unified meshing method is adopted.

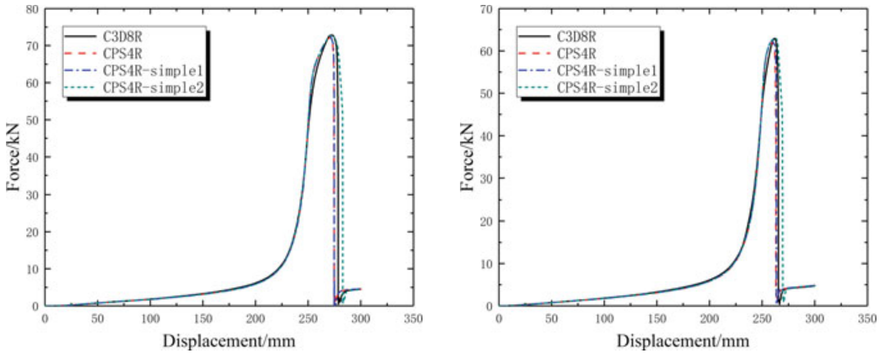
4 Numerical Simulation Study

4.1 Force–Displacement Relationship

The force–displacement is very important to the engineering design of the SRR. Therefore, the effect of modeling methods with different sectional defect rate on the force–displacement was investigated. It can be seen from Fig. 4 that the force–displacement almost completely overlaps before the ultimate state.

4.2 Stress Distribution

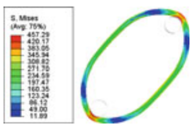
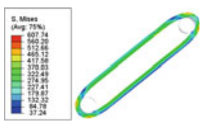
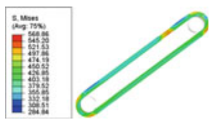
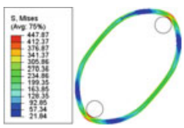
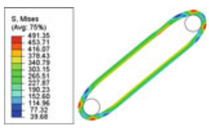
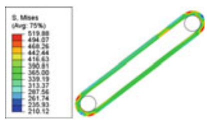
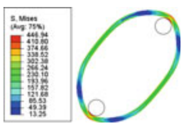
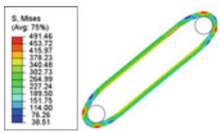
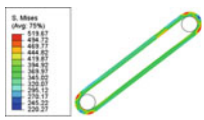
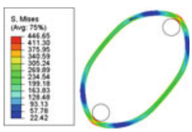
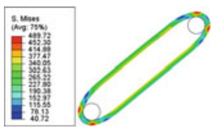
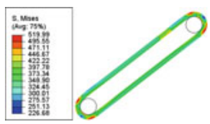
The stress distribution of four types of FE models when the cross-sectional defect rate is 15% are shown in Table 1. In the table, $\delta_1 = 155$ mm, $\delta_2 = 240$ mm, $\delta_3 = 255$ mm, the selected displacements are respectively in the stable stiffness stage, the stiffness gradient stage and the ductile stretching stage [5]. These displacements were selected to compare the stress distribution at the different types of FE models.



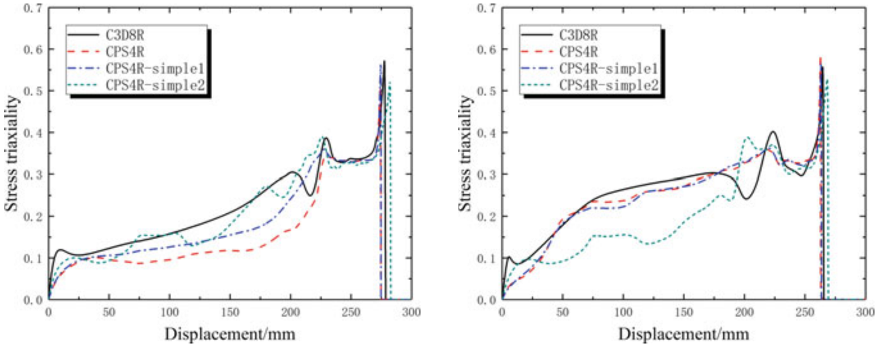
(a) The cross-sectional defect rate:15% (b) The cross-sectional defect rate:30%

Fig. 4 Force–displacement

Table 1 Stress distribution of four model types

Model type	$\delta_1 = 155$ mm	$\delta_2 = 240$ mm	$\delta_3 = 255$ mm
C3D8R			
CPS4R			
CPS4R-simple1			
CPS4R-simple2			

It is shown, in Table 1, that there are minor differences on the stress distribution of four types of FE models.



(a) The cross-sectional defect rate:15% (b) The cross-sectional defect rate:30%

Fig. 5 Stress triaxiality

4.3 Stress Triaxiality

The stress triaxiality can reflect the stress state of the element and affect the fracture failure process [7]. The stress triaxiality of the first fractured element in the finite element model is extracted, and the element is deleted when the stress triaxiality is approximately equal to 2/3. When the cross-sectional defect rate is 15%, the stress triaxiality of CPS4R-simple2 and C3D8R models is relatively close. When the cross-sectional defect rate is 30%, stress triaxialities of CPS4R, CPS4R-simple2 and C3D8R are relatively close. Therefore, for the C3D8R model and the CPS4R model, the stress triaxiality is different when the defect section area is small.

4.4 Analysis Time

The time required for the finite element analysis often depends on the computer configuration and the complexity of the model. For the computer selected by the author, taking a finite element model with a 15% cross-sectional defect rate as an example, it took 55 min to analyze a C3D8R model, it took 6 min to analyze a CPS4R model, and it took 4 min to analyze a CPS4R-simple1 model, while the analysis of a CPS4R-simple2 is only 3 min. Therefore, the calculation efficiency of the CPS4R-simple2 is higher for this paper (Fig. 5).

5 Optimization Model Validation

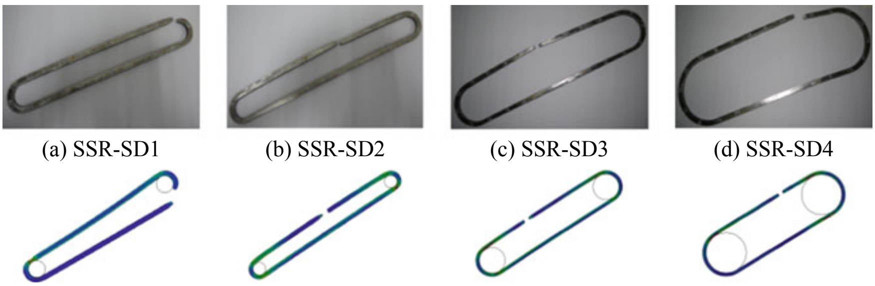
In order to verify the effectiveness of the proposed optimized model, it designed, in this paper, four specimens of the SRR with different parameters to monotonic loading tests. The dimensions of the specimens are shown in Table 2. In which, the A, $A_{\min}$ and α are design cross-sectional area, defect cross-sectional area and cross-sectional defect rate, respectively. In the test, a MTS is used to drive the upper guide pulley to produce a horizontal displacement until the specimen is broken and the lower guide pulley is fixed.

By comparing the final fracture mode of the specimen, it is shown that the CPS4R-simple2 model can be employed to simulate the failure mode of SRRs (Fig. 6).

It illustrated, in Fig. 7, the comparison of force–displacement of the experiment and numerical simulation. The maximum error of the ultimate bearing capacity and ultimate displacement of the experiment results and finite element results are 4.5% and 3.7%, respectively. The force–displacement of the specimen and the FE model are basically same, which proves the validity of the CPS4R-simple2 model.

Table 2 Geometrical dimensions of specimens

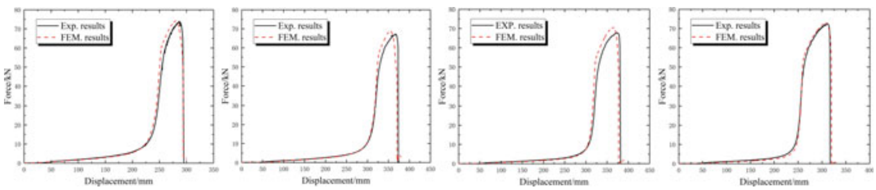
Name	R/mm	D/mm	A/mm	$A_{\min}$/mm	α/%
SRR-SD1	120	40	120	108	10
SRR-SD2	145	40	120	99.6	17
SRR-SD3	170	90	120	98.4	18
SRR-SD4	170	140	120	102	15



(a) SSR-SD1 (b) SSR-SD2 (c) SSR-SD3 (d) SSR-SD4

(e) SSR-SD1FE (f) SSR-SD2FE (g) SSR-SD3FE (h) SSR-SD4FE

Fig. 6 Comparison of failure modes between experiment results and analytical results



(a) SSR-SD1 (b) SSR-SD2 (c) SSR-SD3 (d) SSR-SD4

Fig. 7 Comparison of results from numerical simulation and experiment

6 Conclusions

1. This paper proposes a method for establishing an optimized FE model of the SRR with sectional defects. The validity of the model is proved by comparison with the C3D8R model and test results, and the calculation efficiency is higher. The CPS4R-simple2 model is the best choice for the optimized model of this paper.
2. For the FE analysis of the SRR with sectional defects, the force–displacement and the stress distribution of the analysis results of the C3D8R model and the CPS4R model are almost identical. However, the stress triaxiality is slightly different when the defect section area is small.
3. For the FE model of the SRR with sectional defects using CPS4R, the mesh has little effect on the force and displacement results.

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