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Finite element numerical analysis of pull-out force of hydraulic expansion joint

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Abstract

Taking the steam generator tube expansion joint as the research object, a 3D axisymmetric finite element model was established to calculate the pull-out force of different groove width models under different expansion pressures. Use the relevant standards to verify whether the pull-out force of the expansion joint meets the relevant requirements. By comparing the finite element results under different expansion pressures, the groove width and the expansion pressure with higher pull-out force are founded. This study can provide reference for the determination of the groove width and expansion pressure of the tube sheet during hydraulic expansion.

Keywords

Hydraulic expansion joint; expansion joint; tube plate slot width; pull-out force.

1. Introduction

Studies[1-7] at home and abroad have shown that if appropriately increasing the width L of the tube sheet groove, the sealing pressure and the pull-out force can be increased. After a large number of experiments, Javad[1] et al. obtained the conclusion that the best $L=\sqrt{1.56Rh}$, where "R" is the median diameter of the heat exchange tube and "h" is the thickNess of the heat exchanger tube wall; Updike[2] et al. give $L=(1.2\sim2)\sqrt{Rh}$ The conclusion of Huigeng Yan [3] et al. through the finite element numerical analysis, is that the optimal groove width $L=(1.6\sim1.8)\sqrt{Rh}$. Qing zhu Fan [4] et al. compared the results of finite element simulation and experiment and found that when the groove width is larger than 6mm, the difference between the experimental results and the finite element results is gradually increased. Peixue Li [5] et al. compared the two expansion joints of mechanical expansion and hydraulic expansion, and found that the quality of hydraulic expansion is significantly better than mechanical expansion. Yuqi Ding[6] et al. carried out finite element simulation on the expansion joints of different tube sheets. The results show that the number of surface tube plate slots does not affect the residual contact stress of the grooved area. Ying Wang[7] et al. studied the performance of different groove width expansion joints through experiments. The experimental results show that the double groove structure has the best sealing performance when the groove width is 3 mm. When the groove width is 8 mm, the single groove structure has the best sealing performance.

According to the previous research, this paper uses ANSYS software to carry out finite element simulation analysis on the hydraulic expansion process of the expansion joint with the groove width of 5~8mm, and obtains the residual contact stress of the grooved area of the tube sheet after expansion. The finite element simulation analysis of the expansion joint model after the expansion joint is completed, and the RCC-M standard and the GB151-2014 standard are used to check whether the pull-out force of the expansion joint meets the relevant requirements.

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2. Lap force assessment criteria

Pulling force is one of the important indicators to evaluate the quality of hydraulic expansion joint of expansion joints. According to the requirements of RCC-MF4400 of the French "Code for Design and Construction of Pressurized Nuclear Island Nuclear Equipment", the pull-out force F of the steam generator expansion joint after hydraulic expansion must meet the following requirements:

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$$F \geq \frac{P\pi d i^2}{2} \tag{1}$$

$$F / S_0 \geq \frac{R_{P0.2}}{2} \tag{2}$$

Where F is the pull-off force, P is the maximum different pressure during operation, d_i is the inner diameter of the heat transfer tube, S0 is the nominal cross-sectional area of the heat transfer tube, and $R_{P0.2}$ is the minimum yield strength of the heat transfer tube at 20 °C.

According to the provisions of GB151-2014 "Shell-and-tube heat exchanger", the values of the allowable pull-off force [q] are as follows:

$$F \geq [q]\pi\left(r_o^{\,2} - r_i^2\right) \tag{3}$$

For the steel pipe, the pipe end is not crimped, and the pipe hole is not grooved, [q] = 2 MPa; the pipe end is crimped, and the pipe hole is grooved, [q] = 3 MPa.

If the pull-out force meets the requirements of RCC-MF4400 and GB151-2014, the quality of the expanded joint can be considered to meet the design requirements.

The relevant parameters are r_i=6mm,r_o=8mm,[q]=3MPa,P=19.6MPa,di=6mm, $R_{P0.2}$=205MPa, which can be substituted into formula (1), formula (2) and formula (3). The requirement for the minimum pull-out force of the expanded joint is 9016N.

3. Finite element analysis of the expansion process

The finite element model uses a 3D axisymmetric model to simplify the tube plate to an equivalent sleeve. Since the model is symmetric about the y-axis, the finite element model is reduced to one-twentieth of the sleeve model in order to improve computational efficiency.

3.1 Finite element model size

As shown in Fig. 1, the heat exchange tube has a size of Φ12×2 mm, a tube sheet thickNess of 15 mm, a total heat exchange tube length of 100 mm, and a expansion joint length of 50 mm. The tube plate groove is located at the center of the expansion joint of the tube plate, and the edge and bottom of the tube plate groove are rounded with a radius of 0.25 mm, and the groove width is from 5 mm to 8 mm every 1 mm to establish a model.

3.2 Element type and meshing

The expansion process uses the nonlinear static structure analysis of the multi-load step solution. The three-dimensional model of the steam generator expansion joint uses the SOLID186 solid element in the heat exchange tube and the tube plate, and the contact between the heat exchange tube and the tube plate are established by TARGE170 unit and CONRA174 unit. As shown in Fig. 2, the heat exchange tube model uses the quadrilateral element map to divide the grid. The grid size is controlled by the LESIZE command, and the grid in the slotted portion of the tube sheet is partially encrypted;

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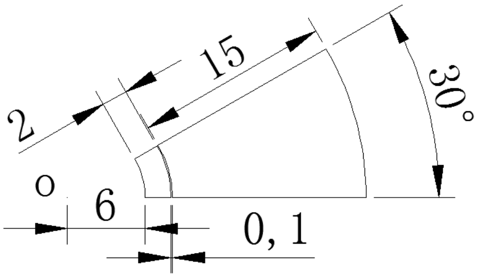
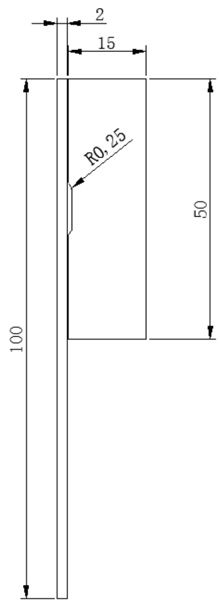
The tube plate are curves and irregular parts, so there is freely meshed by triangular elements, the mesh size is controlled by the LESIZE command, the part near the inner wall of the tube plate hole is partially encrypted, and the mesh at the slot is subjected to secondary local encryption.



a)



b)

Fig. 1 Finite element model size

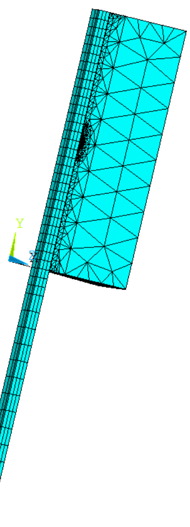


Fig. 2 Finite element model meshing

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3.3 Material properties

The material of the heat exchange tube is SA-213 T22, and the material of the tube sheet is SA-336 Gr. F22CL3. The specific properties of the material are shown in Table 1. The stress-strengthening type of the heat exchange tube and the tube sheet is bilinear stress-strain strengthening, and the friction coefficient is 0.1.

Table 1 Material parameters

	Elastic Modulus	Uensity	Poisson's ratio	Yield Strength	Ultimate strength
Unit	MPa	tonne/mm^3	/	MPa	MPa
SA-213M T22	2.10E+05	7.75E-09	0.3	205	415
SA-336MGr.F22 CL3	2.10E+05	7.75E-09	0.3	207	517

3.4 Contact between heat exchange tube and tube sheet

The TARGE170 target unit and the CONTA174 contact unit are used to establish a 3D face-to-face contact pair between the heat exchange tube and the tube sheet. Since the heat exchange tube and the tube sheet are elastic or plastically deformed during the expansion process, a flexible-flexible contact pair is selected. To simulate the contact between the heat exchange tube and the tube sheet.

As shown in Fig. 3, a contact pair is established between the outer surface of the heat exchange tube and the inner surface of the tube sheet hole, and the blue line indicates the normal line of the contact unit.

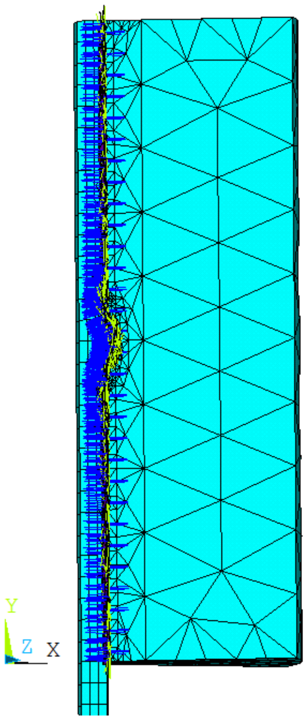

Fig. 3 Contact pair

3.5 Contact between heat exchange tube and tube sheet

3.5.1 Constraint

As shown in Fig. 4, the cross section of the heat exchange tube and the tubesheet (No. 1) are symmetrically constrained. The outer surface of the equivalent plate of the tube sheet (No. 2) constrains all degrees of freedom, and the other faces are free faces, without adding any constraint.

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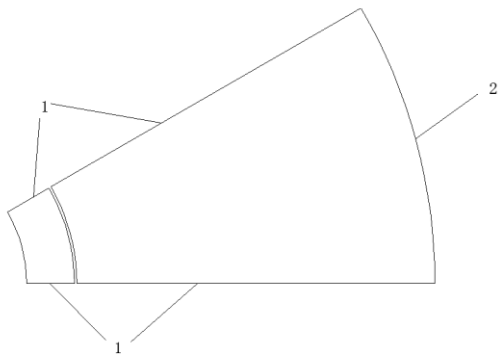

Fig. 4 Contact pair

3.5.2 Load

A uniform expansion pressure is applied to the inner surface of the heat exchange tube (red area in Fig. 5). In order to more realistically simulate the actual expansion process, the application of the expansion pressure is divided into four load steps:

Calculation of initial conditions (load step 1): Time node 1 in Fig. 6 is the calculate process of the initial conditions. Initial conditions need to be set before the formal calculation. The most reliable method is to apply a very small pressure on the inner surface of the heat transfer tube. Calculate the result of the trial calculation as the initial condition of the formal calculation.

Pressurization process (load step 2): The part between time nodes 1 and 2 in Fig. 6 is the pressurization process. The ramp load is more in line with the actual situation of hydraulic expansion and also facilitates convergence, so the pressurization process load the application is carried out using a ramp load. The load settings respectively are 270 MPa, 300 MPa, 370 MPa and 410 MPa.

Holding process (load step 3): The part between time nodes 2 and 3 in Fig. 6 is the pressure holding process, and the expansion pressure of the whole holding process is maintained at the maximum expansion pressure, in order to stabilize the plastic deformation of the heat exchange tube. The load settings respectively are 270 MPa, 300 MPa, 370 MPa and 410 MPa.

Unloading process (load step 4): The portion between time nodes 3 and 4 in Fig. 6 is the unloading process. The application process of the load is similar to the pressurization process, and the expansion pressure is gradually reduced from the maximum expansion pressure to 0 MPa. The load is set to 0 MPa and the loading mode is set to ramp load.In summary, a total of four load steps are used to simulate the entire expansion process, and each load step outputs the results of 10 load substeps equally spaced.

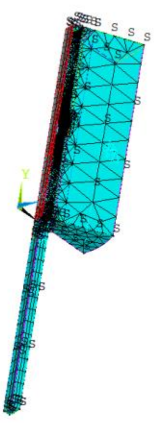

Fig. 5 load application

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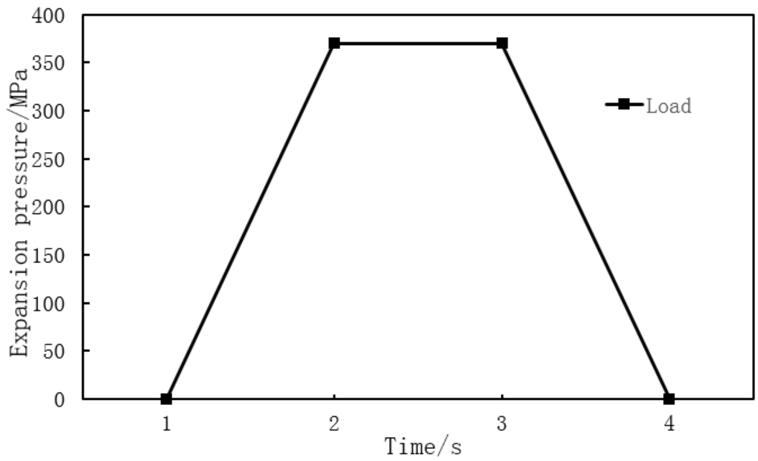

Fig. 6 load application method

3.6 Finite element results of the expansion process

Fig. 7 is the residual contact stress diagram after the expansion of the model with a groove width of 8 mm under the expansion pressure of 270 MPa. It can be clearly seen that the residual contact stress between the heat exchange tube and the tube sheet in the ungrooved area is uniform. Where the heat pipe is in contact with the edge of the tube plate groove, there is a ring of high-stress area, and the heat exchange tube and the bottom of the tube plate groove do not generate residual contact stress, which is consistent with the actual situation.

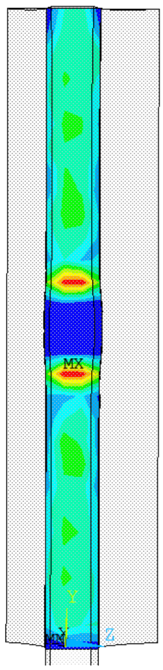

Fig. 7 Residual contact stress of the model with a groove width of 8 mm under 400 MPa expansion pressure

4. Finite element model of the pull process

In order to check whether the pull-out force of the expansion joint meets the assessment criteria of Section 1, the finite element numerical analysis of the finite element model after the completion of the expansion in Section 1 is carried out, and the pull-out force of the expansion joint is calculated. Since the numerical analysis is performed again on the results of the numerical analysis in Section 1, the unit type, material properties, meshing, contact pairs, constraints, and other settings of the finite element model are not changed.

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4.1 Pull load

In actual use, the expansion joint of the steam generator expansion joint is connected by the residual contact stress between the heat exchange tube and the tube sheet. If the residual contact stress of the expansion joint portion is reduced to very small even close to 0 during the pulling process, it is now possible to determine the failure of the expansion joint.

In the pull-off experiment, a small to large pulling force is usually applied to the bottom of the heat exchange tube, and the heat exchange tube is completely pulled out from the tube sheet hole, and the maximum pulling force applied during the pulling process is the pull-out force of the expansion joint. From a safety point of view, when the residual contact stress drop in the ungrooved area is zero, it can be determined that the expansion joint has failed.

The pull-in experiment applies a load by applying a small to large pulling force to the bottom of the heat exchange tube until the heat exchange tubes are all pulled out. In the ANSYS finite element analysis, not only the force load but also the displacement load can be applied. Select the lower end of the heat transfer tube and apply a displacement load of a certain length.

4.2 Pull length

The pull-out process only needs to calculate the residual contact stress of the ungrooved area to be 0. In order to reduce the unnecessary calculation cost, a trial calculation is required before the formal calculation to determine the appropriate pull-off length. Taking the model of the groove width of 8 mm under the expansion pressure of 270 MPa as an example, the load of the pulling process is as follows:

Pull-off process (load step 5): The lower end face of the heat transfer tube model is selected to apply a displacement load of 1 mm in the negative direction (downward) of the y-axis. The time point is set to 5, the initial load step is 1E5, the maximum load step is 1E9, the minimum load step is 1E3, and the results of 10 load substeps are equally spaced.

Fig. 8 is a residual contact stress diagram of the heat exchange tube and the tube sheet with the pull-off length of 0.2 mm. It can be seen that the residual stress of the high stress band on the upper edge of the tube plate groove and the ungrooved area of the tube sheet are significantly reduced, There is still residual contact stress in the most ungrooved area of some of the tube sheets.

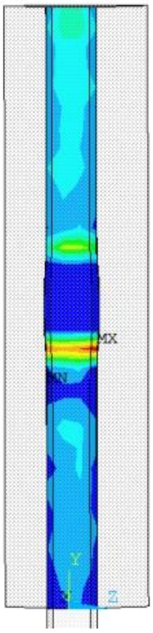

Fig. 8 Residual contact stress after detachment of slot width 8mm under 270MPa expansion pressure

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Fig. 9 shows the residual contact stress diagram of the heat exchange tube and the tube sheet with the pull-off length of 0.3 mm. It can be seen that the residual contact stress of the high stress band on the upper edge of the tube sheet groove is significantly reduced, but most of the tube sheet is not grooved. The residual contact stress is already zero.

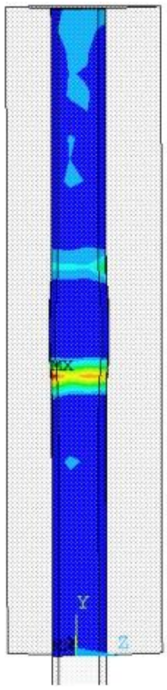

Fig. 9 Residual contact stress after detachment of slot width 8mm under 270MPa expansion pressure

Fig. 10 is a residual contact stress diagram of the heat exchange tube and the tube sheet with the pull-off length of 0.4 mm. The residual contact stress of all the unslotted areas of the tube sheet has been 0, and the expansion joint failure can be determined at this time.

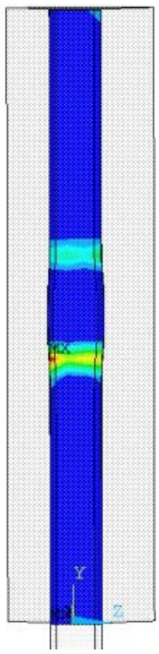

Fig. 10 Residual contact stress after delamination of 8mm model pull-off 0.4mm in 270MPa expansion joint pressure

In order to check whether the groove width has an influence on the pull-off length, the model with a groove width of 5 mm, 6 mm and 7 mm under the expansion pressure of 270 MPa was tested, and the

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pull-off length of the expansion joint failure was 0.4 mm. The tube plate slot width does not affect the pull length.

In order to check whether the expansion pressure has an influence on the length of the pull-off, the model with a groove width of 8 mm under the expansion pressure of 300 MPa, 370 MPa and 410 MPa is tested. The length of the expansion joint failure is 0.4 mm, 0.5 mm. And 0.5mm. It can be seen that the length of the pull-up increases as the expansion pressure increases.

In summary, the maximum pull-off length for the expansion joint failure is 0.5 mm. In order to avoid the pull length of the individual model exceeding 0.5 mm, the pull-off length of the pull-off process was set to 0.6 mm.

4.3 Pull step setting

The final determined pull load step is as follows:

Pull-off process (load step 5): The lower end face of the heat transfer tube model is selected to apply a displacement load of 0.6 mm in the negative direction (downward) of the y-axis. The time point is set to 5, the initial load step is 1E5, the maximum load step is 1E9, the minimum load step is 1E3, and the results of 10 load substeps are equally spaced.

5. Finite element results of pull force

The numerical analysis of the pull-off process is to apply a displacement load on the lower end of the heat exchange tube. During the movement of the heat exchange tube, ANSYS calculates the force on the lower end surface that just causes the heat transfer tube to move, so the maximum of the lower end of the pull-off process 12 times the reaction force (this model uses the 1/12 model) is the pull-out force of the expansion joint. The finite element results are shown in Table 2. The pull-out force of all models is above 12kN, which meets the requirement of not less than 9.016kN in the first section.

Table 2 Finite element model pull-off force (unit kN)

Slot width /mm / Expansion pressure /MPa	5	6	7	8
270	12.71999	13.84982	13.02037	13.66866
300	13.66026	15.62618	14.61944	15.08148
370	15.03319	16.32336	16.26246	16.31455
410	15.31427	16.73444	16.44471	16.88382

5.1 Comparison of finite element results of different groove width models under the same expansion pressure

To more intuitively show the differences between the different models, the data in the table is plotted as a line chart for comparison.

Fig. 11 shows the pull-out force of the 5~8mm groove width model under 270MPa expansion pressure. The pull-out force of the model with the groove width of 6mm is the largest, and the pull-out force of the model with the groove width of 5mm is the smallest. The difference between the maximum and minimum values is about 1.13kN.

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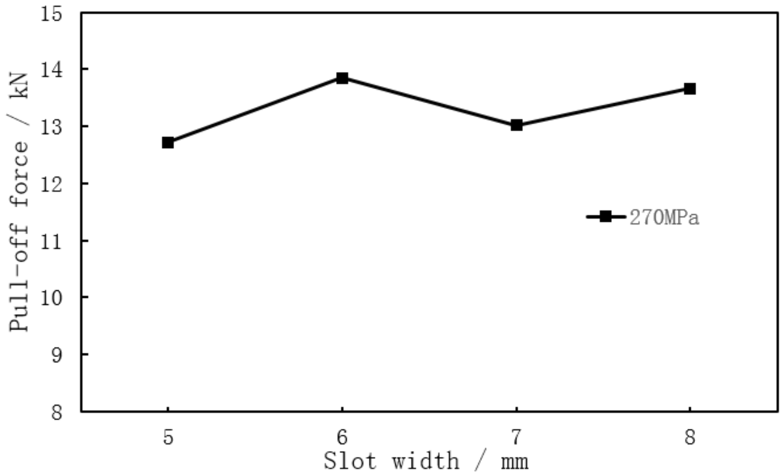

Fig. 11 Pull-off force of different groove width models under 270MPa expansion pressure

Fig. 12 shows the pull-out force of the 5~8mm groove width model under 300MPa expansion pressure. The pull-out force of the model with the groove width of 6mm is the largest, and the pull-out force of the model with the groove width of 5mm is the smallest. The difference between the maximum and minimum values is about 1.97kN.

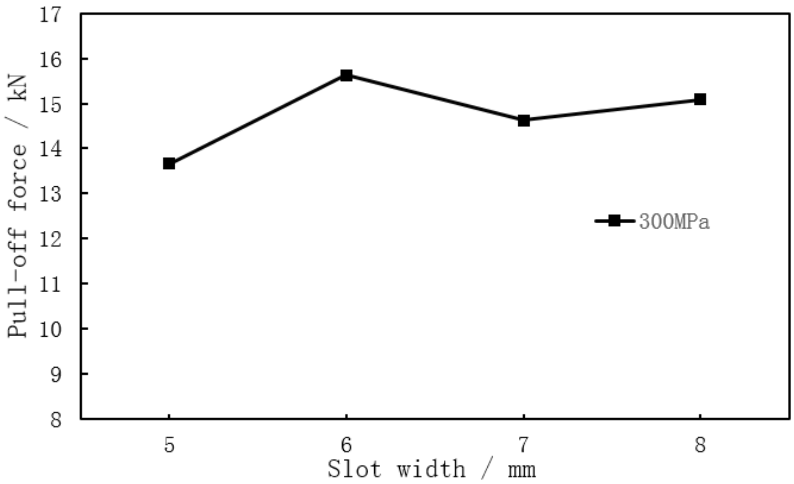

Fig. 12 Pull-off force of different groove width models under 300MPa expansion pressure

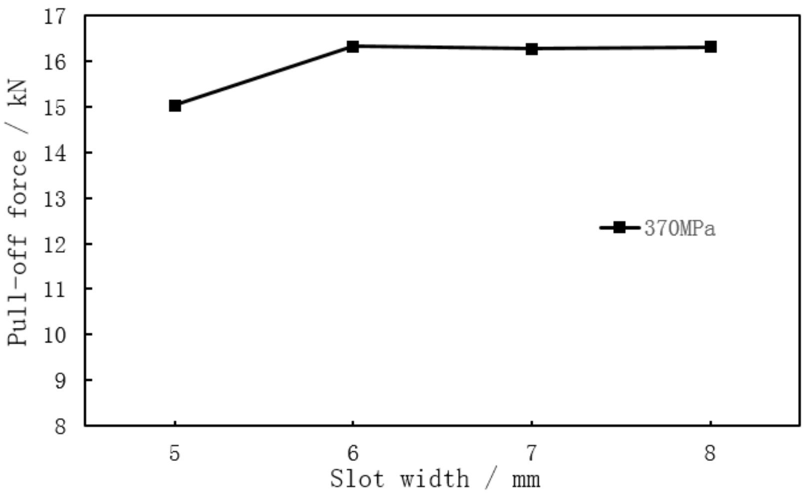

Fig. 13 Pull-off force of different groove width models under 370MPa expansion pressure

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Fig. 13 shows the pull-out force of the 5~8mm groove width model under the expansion pressure of 370MPa. The pull-out force of the model with the groove width of 6mm is the largest, the pull-out force of the model with the groove width of 5mm is the smallest, and the pull-out force of the 6mm, 7mm and 8mm groove width models is very close, and the difference between the maximum and minimum values is about 1.97kN.

Fig. 14 shows the pull-out force of the 5~8mm groove width model under the expansion pressure of 410MPa. The pull-out force of the model with the groove width of 8mm is the largest, the pull-out force of the model with the groove width of 5mm is the smallest, and the pull-out force of the 6mm, 7mm and 8mm groove width models is relatively close, and the difference between the maximum value and the minimum value is about 1.57kN.

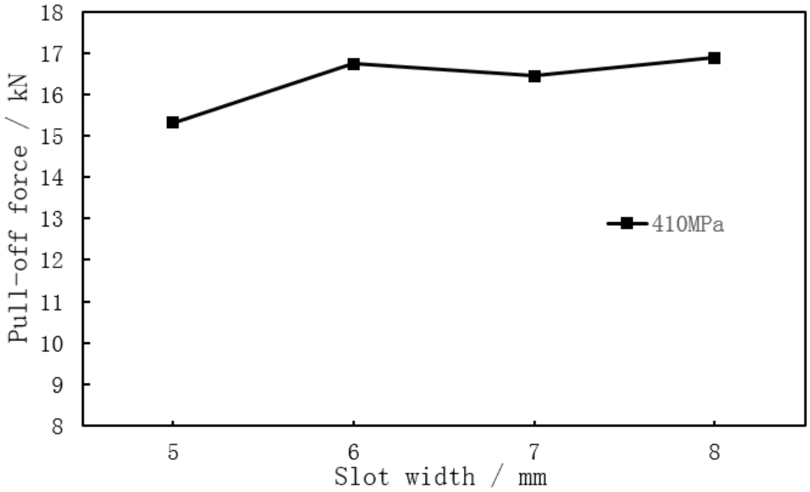

Fig. 14 Pull-off force of different groove width models under 410MPa expansion pressure

5.2 Comparison of finite element results of the same groove width model under different expansion pressures

Fig. 15 shows the pull-off force of the 5mm groove width model under different expansion pressures. The pull-out force increases with the increase of the expansion pressure. The pull-out force is the smallest when the expansion pressure is 270MPa, and the maximum pull-out force when the expansion pressure is 410MPa. The difference between the value and the minimum is approximately 2.59kN.

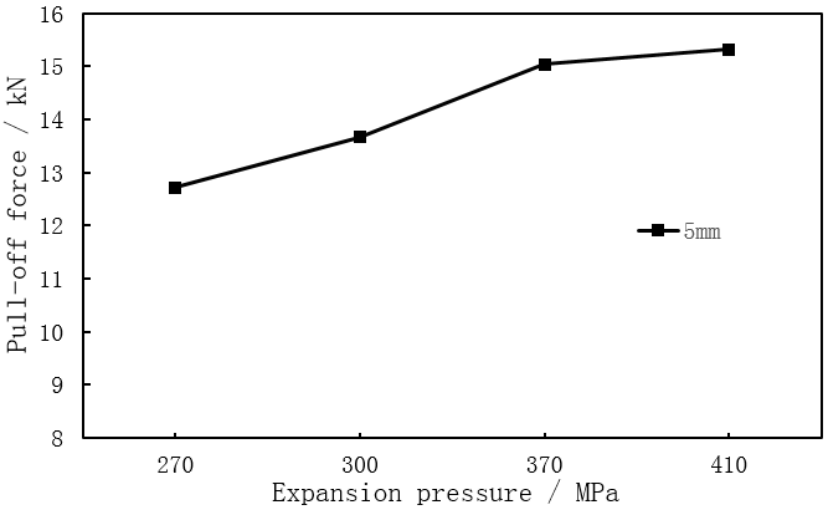

Fig. 15 Pull-out force under different expansion pressures of the model with a groove width of 5 mm

Fig. 16 shows the pull-out force of the 6mm groove width model under different expansion pressures. The pull-out force increases with the increase of the expansion pressure. The pull-out force is the

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smallest when the expansion pressure is 270MPa, and the maximum pull-out force when the expansion pressure is 410MPa. The difference between the value and the minimum value is approximately 2.88 kN.

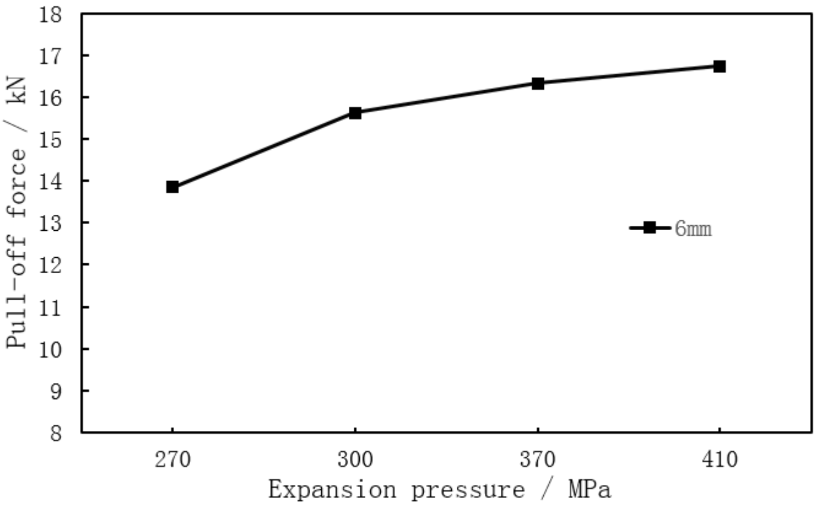

Fig. 16 Pull-out force under different expansion pressures of the model with a groove width of 6 mm

Fig. 17 shows the pull-off force of the 7mm groove width model under different expansion pressures. The pull-out force increases with the increase of the expansion pressure. The pull-out force is the smallest when the expansion pressure is 270MPa, and the maximum pull-out force when the expansion pressure is 410MPa. The difference between the value and the minimum value is approximately 3.42 kN.

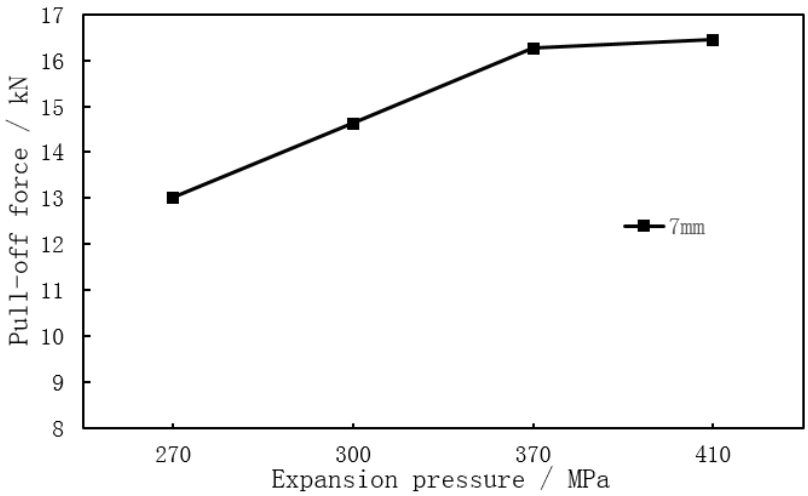

Fig. 17 Pull-out force under different expansion pressures of the model with a groove width of 7 mm

Fig. 18 shows the pull-out force of the 8mm groove width model under different expansion pressures. The pull-out force increases with the increase of the expansion pressure. The pull-out force is the smallest when the expansion pressure is 270MPa, and the maximum pull-out force when the expansion pressure is 410MPa. The difference between the value and the minimum value is approximately 3.21 kN.

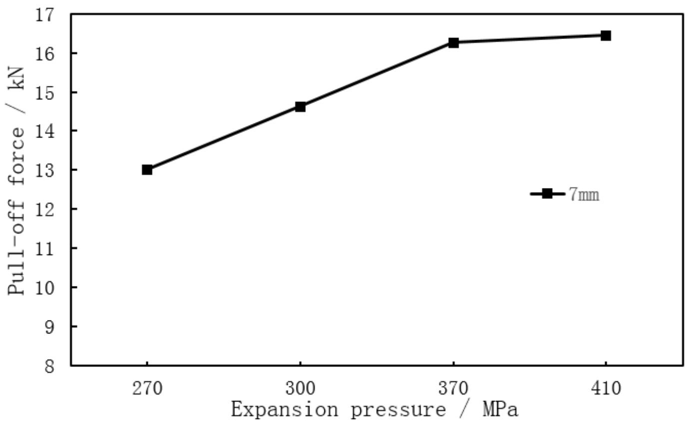

Fig. 18 Pull-out force under different expansion pressures of the model with a groove width of 8 mm

6. Conclusion

Based on the finite element results in Section 4, the following conclusions can be drawn:

When the slot width is constant, the pull-out force increases as the expansion pressure increases.

Under the expansion pressure of 270MPa and 300MPa, the pull-out force of the expansion joint with the groove width of 6mm and 8mm is larger; under the expansion pressure of 370MPa and 410MPa, the pull-out force of the expansion joint with the groove width of 6mm, 7mm and 8mm is relatively close. .

Under the four kinds of expansion pressure, the pull-out force of the expansion joint with the groove width of 5mm is the smallest.

AckNowledgements

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