Thermal stress analysis of cryogenic adhesive joints for non-magnetic dewar

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The thermal stress analysis of screwed-adhesive joints of the non-magnetic Dewar was carried out in this paper. The serious stress concentrations occurred at the adhesive free ends and the external thread roots of the lower adhesive joint. The effects of LN_2 volume fraction and screw pitch on the stress distribution of the adhesive joints were discussed. The results provide some important references for the design of the non-magnetic Dewar.

INTRODUCTION

SQUID is the most sensitive magnetometer which can detect 10^{-16}T magnetic field. It has been widely applied in earth magnetism detection, nondestructive examination, scanning SQUID microscope, satellite, etc. The non-magnetic Dewar can provide the cryogenic and non-magnetic environment which is necessary for SQUID. The different parts of the non-magnetic Dewar mainly made of glass fiber reinforced plastics (GFRP) are adhesively bonded. The brittleness of adhesive will increase at cryogenic temperatures. In addition, the differences of the thermal expansion coefficients and Young's moduli of adhesive and adherends can produce high thermal stress when temperature changes. These may cause adhesive crack and destroy the vacuum tightness. Therefore, it's necessary to perform the thermal stress analysis of the adhesive joints.

Although many studies on thermal stress analysis of adhesive joints have been reported, the thermal stress analysis at cryogenic temperatures is very rare. Takao and Qiang [1] tested the strength of the adhesive joint between metal and FRP and carried out thermal stress analysis in 1991. Gorbatkina and sulyaeva [2] investigated the effect of cyclic cooling from ambient temperature down to liquid nitrogen (LN_2) temperature on the shear adhesive strength of fiber/polymer joints.

Since the adhesive joints in the non-magnetic Dewar require high strength and high vacuum tightness, the screwed-adhesive joint, rectangular thread-adhesive joint and bellows-adhesive joint are applied in the non-magnetic Dewar. However, the thermal stress analysis of these adhesive joints has not been reported. Thus, the present work is to carry out thermal stress analysis for the screwed-adhesive joint used extensively in the non-magnetic Dewar at cryogenic temperatures, and discuss the effects of LN_2 volume fraction and screw pitch on the stress distributions of the adhesive joints. The results provide some important references for the design of the non-magnetic Dewar.

JOINT CONFIGURATION AND FINITE ELEMENT MODEL

The main dimensions of the non-magnetic Dewar and screwed-adhesive joints are shown in Figure 1. An adhesive thickness t=0.2mm was applied in the study. The screw pitch was 1.5mm for the first analysis. In production of adhesively bonded joints, the adhesive layer is squeezed out and accumulated around the free ends of the adhesive layer, called adhesive fillets. It has a considerable effect on the peak adhesive stresses arising at the adhesive free ends. Here, the shape of adhesive fillet was idealized to a triangle with a height and a width twice the adhesive thickness (f_t=0.4mm). In order to avoid the stress singularities, the corners of adherends were rounded with a radius r of 0.2t [3] as shown in Figure 1. The pitch angle of the screwed-adhesive joints in the non-magnetic Dewar usually is less than 2° . In this case, the effect of the pitch angle on the load distribution along threads can be neglected [4]. Therefore, the thermal stress analysis can be simplified to a two-dimensional axi-symmetrical problem.

The finite element software ANASYS 8.0 was used for the thermal stress analysis. An eight-noded quadrilateral axi-symmetric plane element was used to model the Dewar. Since the stress distribution in the adhesive region changes greatly, the mesh of the adhesive was refined as shown in Figure 2. The sequential coupling method was used to solve the thermal stress problem. The main properties of adhesive and GFRP was from literatures [1, 3].

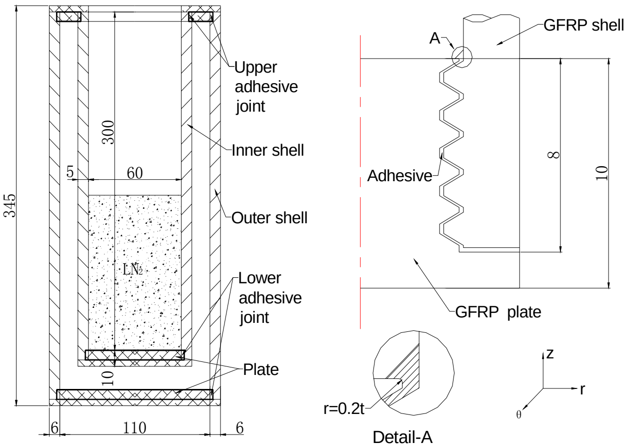


Figure 1 Dimensions of the Dewar and Joints

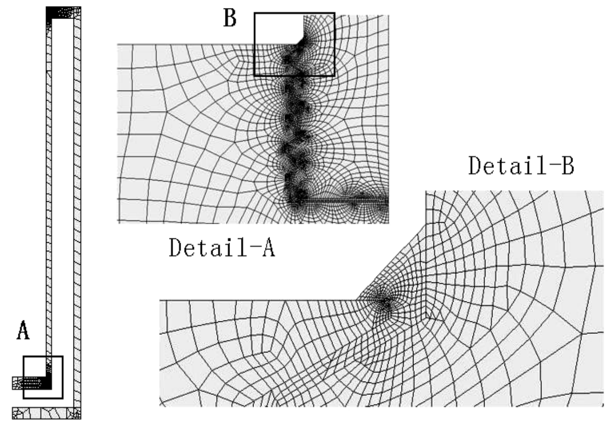


Figure 2 Mesh details of the FEM model of the Dewar

THERMAL ANALYSIS AND STRESS ANALYSIS

Thermal analysis

The screwed-adhesive joint experience the thermal load caused by the LN_2 in the Dewar. The LN_2 volume fraction was assumed to be 80% in the first analysis. The thermal boundary conditions are as follows: the outer surface of the outer shell exposes to air at 300K, and the lower part of the inner surface exposes to LN_2 at 77 K and the upper part exposes to nitrogen whose temperature distribution is linear from 77K to 250K. The steady thermal analysis was carried out and the temperature distribution calculated is shown in Figure 3. It can be found that the great temperature gradient occurs at the upper ends of the inner shell. The decrease of temperature of the lower joint is much larger than that of the upper.

Stress analysis

The shells of the Dewar experience three loads, the thermal load obtained from thermal analysis, the weight of LN_2 and the atmospheric pressure. The applied structural boundary condition is that the outer surface of the bottom of the Dewar was fixed in the z-direction. In the analysis, the joint members, i.e. GFRP shells and plates and adhesive, were assumed to have linear elastic properties at cryogenic temperatures.

The radial stress distributions of the upper and lower screwed-adhesive joints are compared in Figure 4. Figure 4 (a) is for the upper adhesive region and Figure 4 (b) is for the lower adhesive region. It is found that the stress in the lower adhesive region is larger than that in the upper, because the temperature difference of the lower adhesive joint is much greater than that of the upper. The serious stress concentrations occur around the adhesive free ends of both the upper and lower adhesive joints. In addition, the high stress is observed at the external thread roots of the lower screwed-adhesive joint and is more evident through thread close to the bottom of the joint. Similarly, the GFRP also experiences stress concentrations in the corresponding regions. However, the stress distribution in upper adhesive joints is relatively even.

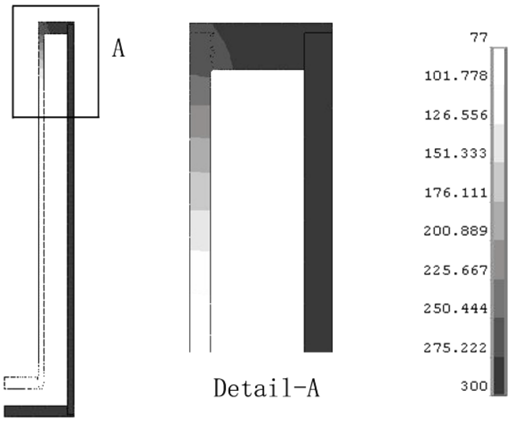


Figure 3 Temperature distribution of the Dewar

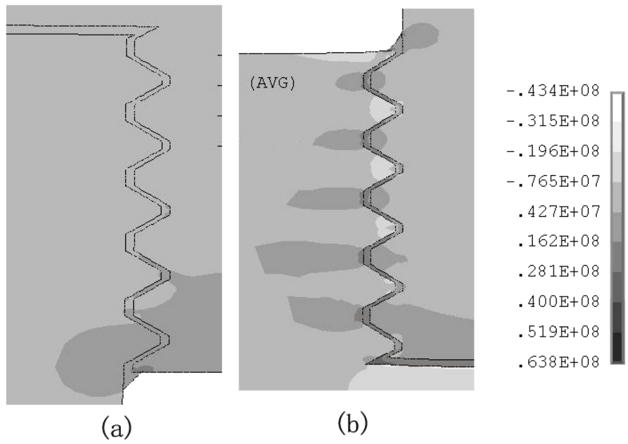


Figure 4 Comparison of σ_{rr} distribution for upper and lower joints

The stress distributions of different directions of the lower adhesive joints were investigated. Figure 5 (a), (b) and (c) are the radial σ_{xx}, hoop $\sigma_{\theta\theta}$ and shear σ_{rz} stress distributions of the lower adhesive region, respectively. From Figure 5 and Figure 4 (b), it is found that the normal stress σ_{zz} is dominant while the radial σ_{xx}, hoop $\sigma_{\theta\theta}$ and shear σ_{rz} stresses are similar, but still serious level. The stress concentrations are observed at the adhesive free ends for all the directions. The distributions of the normal σ_{zz} and hoop $\sigma_{\theta\theta}$ stresses along the thread are relatively even while distributions of the radial σ_{rr} and shear σ_{rz} stresses change greatly. The shear σ_{rz} stress reaches higher level through the thread close to the top of the joint. Since the high stress concentrations occur around the adhesive free ends and external thread roots, the distributions of the radial σ_{rr} and normal σ_{zz} stresses of free ends and the first thread of the lower screwed-adhesive joint are plotted in Figs. 6 (a) and (b), respectively.

As a result, it is concluded that the free end of the lower adhesive joint is the most critical region of the whole Dewar. The high stress occurs at the external thread roots of the lower screwed-adhesive joint and is more evident close to the bottom of the joint.

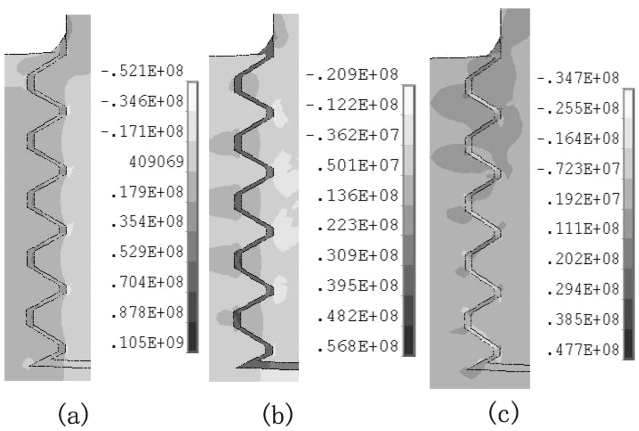


Figure 5 σ_{zz}, $\sigma_{\theta\theta}$ and σ_{rz} distribution of lower region

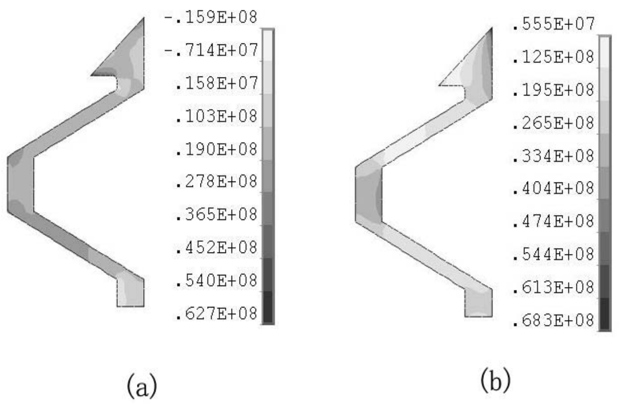


Figure 6 σ_{rr} and σ_{zz} distribution near the fillet for lower joints

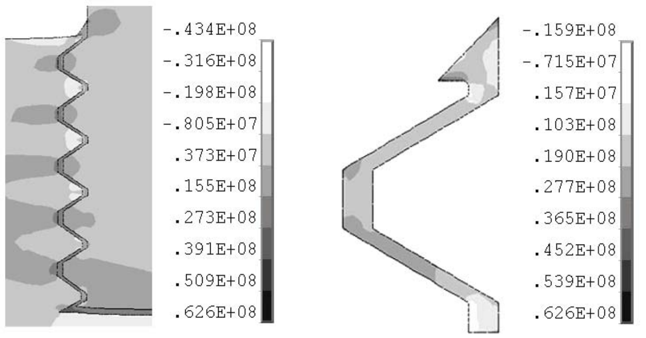
EFFECTS OF LN_2 VOLUME FRACTION AND SCREW PITCH ON STRESS DISTRIBUTIONS

Effect of LN_2 volume fraction on stress distributions

The LN_2 volume decreases continuously during the usage process. Hence, the effect of fraction of LN_2 volume on stress distribution was studied. The radial stress distribution of the lower adhesive joint for 40% LN_2 is shown in Figure 7. Compard Figure 7 with Figure 4 (a), it is found that the stress distribution of the lower adhesive joint hardly changes. This is because the temperature difference which causes thermal stress changes very little when LN_2 volume fraction decreases. Therefore, it can be drawn that the effect of LN_2 volume fraction on stress distribution in the adhesive region is very minor.

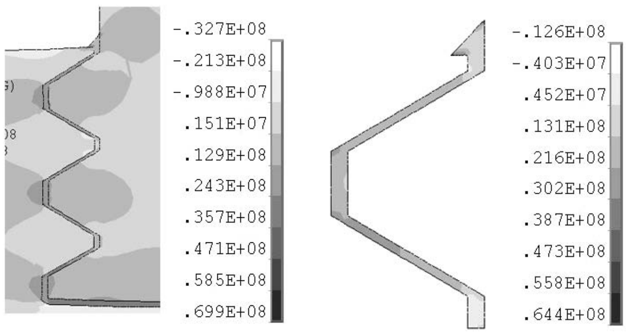
<u>Effect of screw pitch on stress distributions</u>

The screw pitch is an important parameter of the screwed-adhesive joint. The stress distribution for 3 mm screw pitch under same thermal and mechanical boundary conditions is plotted in Figure 8. In case of the 3mm screw pitch, the stress distribution is very similar to that of 1.5 mm screw pitch, and is relatively higher. The main stress concentration occurs at the free end of the adhesive and the stress at external thread root is larger than that of other places of thread.



(a) (b)

Figure 7 σ_{rr} stress distribution for 40% LN_2 volume fraction



(a) (b)

Figure 8 σ_{rr} stress distribution for 3mm screw pitch

CONCLUSION

In this study, the thermal stress analysis of screwed-adhesive joints of the non-magnetic Dewar was carried out. The serious stress concentrations occur in the adhesive free ends, and the stress of the lower adhesive joint is higher than that of the upper. Thus, the most critical region is the adhesive free end of the lower adhesive joint of Dewar. Besides, the stress at the external thread roots of the lower adhesive joint is larger than that of other places of the thread. Increase of screw pitch will increase the stress slightly whilst the stress distribution keeps similar. The LN_2 volume fraction has negligible effect on the stress distribution of the adhesive joints. The results reported in this study can provide some important references to the design of the non-magnetic Dewar.

REFERENCES:

1. Mori, T., Yu, Q., Takahana S., Shiratori M., Low temperature strength of metal-FRP bonded joints, <u>JSME Int. J. Ser I: Solid Mech.</u> (1991), <u>34</u> 257-263
2. Gorbatkina, Y .A., Sulyaeva, Z. P., Strength of the fiber/thermoplastic-matrix interface under cyclic cooling to low temperatures, <u>Compos. Sci. Technol.</u> (1997), <u>57</u> 995-1000
3. Apalak, M. K., Günes, R., Fídanci, L., Geometrically non-linear thermal stress analysis of an adhesively bonded tubular single lap joint, <u>Finite Elem. Anal. Des.</u> (2003), <u>39</u> 155-174
4. Zhao H., Analysis of the load distribution in a bolt –nut connector. <u>Comput. Struct.</u> (1954), <u>53</u> 1465-147