The interface debond analysis for sandwich beam with viscoelastic core and steel faceplates

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Abstract a interface debond phenomenon appeared between viscoelastic core and steel faceplates when unloading in large deflection 3-point bending experiments for sandwich beam. From analysis of loading and unloading process, a reason of debond is found that it is the large deflection cause the debonding of interface firstly under the effect of shear stress. After unloading, local plastic rotation in the middle of beam lead to residual moment between upper faceplate and bottom faceplate. And the shear stress effect at interfaces is also transformed to tension stress. By double cantilever beam and single cantilever beam experimental results, a calculation method of critical deformation are given to calculate the critical strain energy release rate. then the critical crack length values of different types of the specimen are obtained.

Keywords Sandwich, Viscoelastic Core, Debond , Interfacial crack

1. Introduction

The sandwich plate structure with viscoelastic core is often used as bending components, and more and more applied in practical engineering. Characteristics of crack in viscoelastic plate is widespread concerned[1]-[3]. In this paper, the steel sandwich faceplate specimen with polyurethane viscoelastic elastomer core is tested by using of three-points bending experiments and found that due to the interface material property differences between the faceplate and the core, when the specimen is loaded in large deflection and then unloaded, it leads to delay debond phenomenon of crack for lower interfacial strength specimen. By double cantilever beam and single cantilever beam experimental results, a calculation method of critical deformation are given to evaluate the specimen damage, and determine the critical failure condition of specimen.

2. Three-points bending test

The three-points bending test for polyurethane elastomer steel sandwich plate structure is carried out according with the specification "Sandwich Plate Bending Experiments Norms". Bending strength, shear strength, bending rigidity and shear rigidity of the sandwich structure can be determined through three-points bending test. Thereby the modulus of elasticity and the shear modulus of core can be determined too. The shape of cross-section of specimen is rectangular, the thickness of sandwich core is about 11mm, and the faceplates have a thickness of 2 mm, which is shown in Figure 1.

Four different types of specimen are selected by different preparation methods and hardness of the core, which is numbered as No. 1 to No. 4 respectively. Preparation method of No. 1, 2 and 4 is directly pouring, and No. 3 specimen is the one prepare the elastomer core first, then use a strong glue to paste the faceplate and core together. Fig.2 is deflection-load curve of three-points bending experiments of sandwich plate specimen.

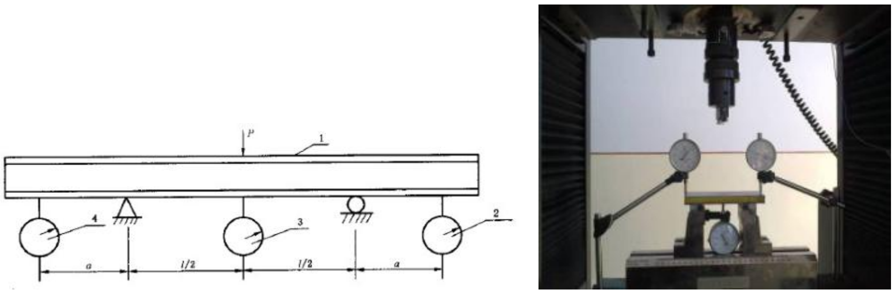


Fig.1 Three-points bending test

Table.1 Parameters and results for three-points bending tests

Specimen No. Item	1	2	3	4
Weight（g）	364.80	385.40	384.50	386.60
Hardness（D）	29	47	51	48
length（mm）	149.84	149.9	150.20	149.90
width（mm）	59.90	59.84	60.60	59.92
Thickness（mm）	13.86	15.64	16.04	14.52
Faceplate thickness（mm）	2. 00	2. 00	2. 00	2. 00
Preparation	Pouring	Pouring	Stick	Pouring
Debonding load（N）	1500	2100	5200	2350
Proportional limit load （N）	1200	1700	2600	1550
Failure load（N）	2600	3400	7000	3600
The maximum load deflection	11.37	12.55	30.02	15.23
Maximum stress (MPa)	26. 27	28. 00	60. 44	36. 90

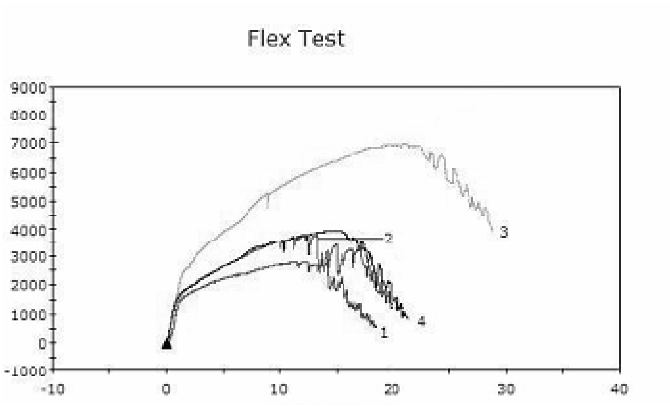


Fig.2 Deflection-load curve for sandwich plate

Observing the whole loading process of three-points bending test of Fig.2, it can be found that the destruction process can be roughly divided into three stages:

1) elastic deformation stage.

In the initial stage of loading, the faceplates and an elastomer core are in the elastic deformation, the internal stress of faceplates distributes uniformly. The faceplates bear the main bending effect, while the core is mainly responsible for shearing effect.

2) Strengthening stage.

When bending stress of faceplates reach the yield limit of the material, plastic hinge appears at the position where the crosshead contact with specimen, and the faceplates rotate around the hinge. In this stage, load-displacement curves rise slowly, on the one hand, this is because the plastic deformation of faceplate, on the other hand, it is because the specimen is constrained by horizontal reaction force at the supports due to deformation increases.

3) Failure stage.

Downward burr will appear on the load-displacement curve when the strengthening phase to a certain extent. As the increasing of load, the more burrs appears. This is because of the phenomenon of debonding between the faceplate and the core. If shear strength between the core and faceplate is smaller, there will be cracked firstly at the corner of the end position. The load curve gradually become horizontal, and great deformation of the faceplates appear along the central plastic hinge zone.

From the breakage of pouring specimen, it can be seen that the failure models of sandwich beam are large bending deformation destruction and shear failure of the interface between the steel faceplate and the polyurethane elastomer core. Such damage often occurs on the upper faceplate, but not obvious when loading. Delayed cracking phenomenon appears when unload. The so-called delayed fracture phenomenon is when the loading displacement reaches a certain limit then unloads, there is no obvious crack propagation at the beginning, but after a while, the crack propagates. For the specimens with weak bonding strength, debonding phenomenon on the upper faceplate will appear; and for the specimens with strong bonding strength, tears of the core occurs at the position of 1/3 length from the edge of the specimen. This is because a large plastic deformation of faceplates causes differences between two faceplates. When unload the specimen, the rebound effect from difference rotate angle between two faceplates make tension stress on the crack surface. When the stress is big enough, and the crack length is reach a certain value, the crack will propagate. For the viscoelasticity of polyurethane core, the crack will not propagate immediately, but for a certain time.

3 strain release rate calculation method of crack when unloading

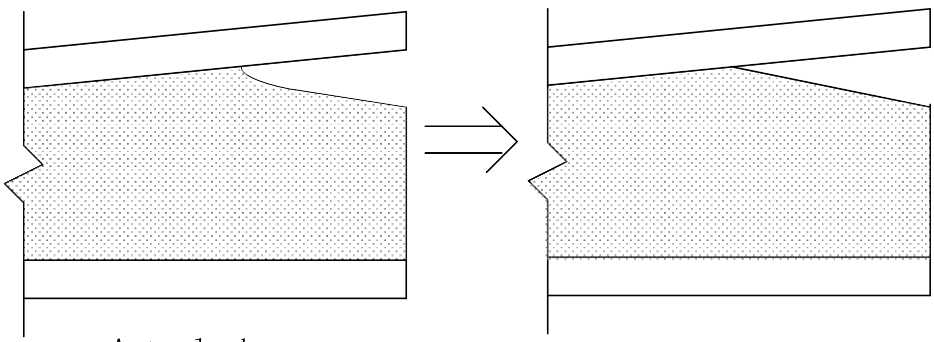
In three-points bending test, the shearing of the vertical load result in the generation of initial crack in the edge, the bending moment when unloading is the main factors of generate crack propagating. Since the core is viscoelastic material, the crack propagation in the interface of sandwich plate faceplate having a certain rate, and it sustain for a period of time with energy release in whole process. For isotropic viscoelastic material crack growth studies have been carried out [4], but in most cases of interface viscoelastic crack with different material, corresponding principle is no longer suitable for use. For the complexity from the singularity of the stress field of viscoelastic material interface crack, there is no effective method to solve the problem[5]. The method of this paper is constructed on the simplifications on the followings:

1) Using the critical strain energy release rate of crack to describe the debonding propagation.

2) Type I and II crack critical is obtained in case of not considering the viscoelasticity of the core material. In order to avoid the viscoelastic effect, the experimental process will last a long time. Due to the polyurethane elastomeric material is typical Kelvin solid, so there must be a limit for crack propagation, when the stress or strain energy release rate is less than this limit, the crack does not propagate; when it is greater than this limit, no matter how long the time last, cracks will propagate inevitable.

3) Through observation, crack tip was found that, because the big difference on the elastic modulus between faceplate material and viscoelastic core, when the crack propagate, there is local deformation of interface crack. The crack morphology is shown in Fig. 3a, and we simplify the deformation curve as a straight line shown in Fig. 3b.

4) Because the modulus of elasticity of the core material is low, but the deformation is large, so the stress along the direction of sandwich thickness of core is assumed uniform distribution.



a Actual shape of crack

b Simplified shape of crack

Fig.3 The simplified crack

Crack strain energy release rate can be written as:

$$G = \frac{1}{b}\left(\frac{dU_e}{da} - \frac{dU_s}{da} \right) \tag{1}$$

G is crack strain energy release rate, *b* is the specimen width, *a* is the crack length, U_e and U_s are stored strain energy and external forces work done. As shown in Figure 4，the cracking process is assumed that crack opening angle is constant in the interface crack growth, corresponding extended strain energy release rate is the critical strain energy release rate. The classical fracture mechanics has proven the crack opening displacement and strain energy release rate are equivalent, and here we make this assumption too. Simplification of the crack propagation process is shown in Figure 4:

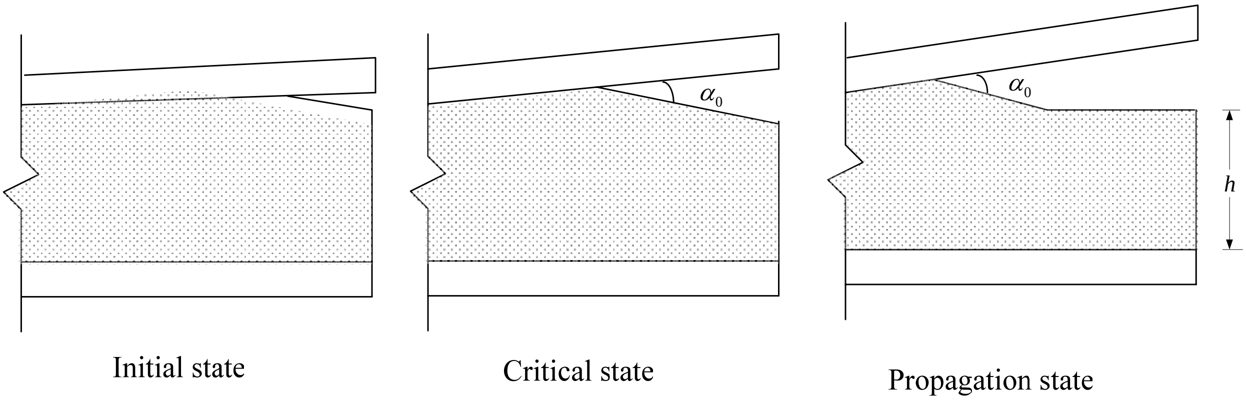


Fig.4 The simplified crack of propagation

For the initial open stage, the crack open angle gradually becomes larger and larger. In the critical state of crack, the core on the right of crack gradually unloaded to the original state, in which the internal stress is 0. In the propagation state of the crack, the crack tip angle unchanged, the right part of crack is not affected by the crack. Only core material of oblique line part is affected. Flat part unloads completely with no stress.

Take the critical state of the cracks to analyze, when crack propagate the length of δa, the corresponding angle of the upper faceplate is β_0, which increase the $\Delta\beta$. Its geometry is shown in Figure 6. When crack extended forward, the flat segment is negligible. Shaded part in Figure 5 is the sandwich viscoelastic core material, the crack extended to point *B2* from point *B1* , crack propagation angle remains unchanged, that is $\angle AB1A1 = \angle AB2A2$,*CA2=B1A1*.

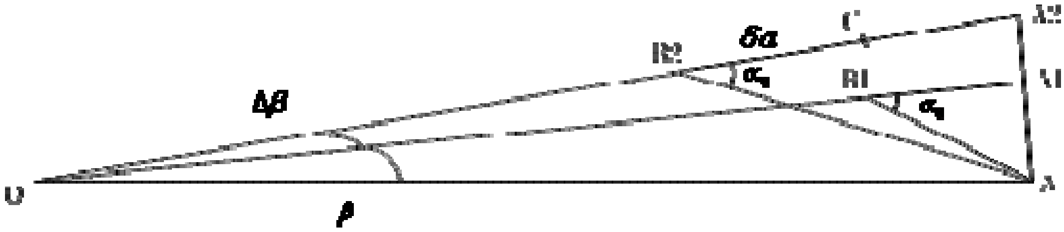


Fig.5 Geometrical relationship of crack propagation

Calculation parameters of the Figure 5, where: the length of *AA2* is $b\sin\left(\frac{\beta+\Delta\beta}{2}\right)$, the length of *AA1* is $b\sin\left(\frac{\beta}{2}\right)$, With the law of sines, we can get length of *B1A1* is $b\sin\frac{\beta}{2}\cos\left(\alpha_0 - \frac{\beta}{2}\right)l\sin\alpha_0$, which is also the initial length of the crack:

$$a = l\cdot\sin\frac{\beta}{2}\cos\left(\alpha_0 - \frac{\beta}{2}\right)\cdot l\sin\alpha_0 \qquad (2)$$

To calculate the variation availables on both sides of the equation, we can get:

$$\delta\beta = \frac{2\sin\alpha_0}{l\cos(\beta - \alpha_0)}\delta a \tag{3}$$

If recover moment can be seen as external forces, external work done is:

$$U_s = M\Delta\beta \tag{4}$$

So the length of *A2B2*:

$$l\sin\frac{\beta}{2}\cos\left(\alpha_0 - \frac{\beta}{2}\right)l\sin\alpha_0 + \delta a \tag{5}$$

Also relationship between crack propagation length and angle changes can also be obtained from the law of sines:

$$\delta a = \frac{l\cos\left(\alpha_0 - \frac{\beta+\Delta\beta}{2}\right)\sin\frac{\beta+\Delta\beta}{2} - b\sin\frac{\beta}{2}\cos\left(\alpha_0 - \frac{\beta}{2}\right)}{\sin\alpha_0} \tag{6}$$

The change of internal energy can be embodied by calculating shaded area differences of bond stress:

$$U_e = \frac{l}{4}b\sigma_{bs}\left[\left(\frac{l}{2} - \delta a - a\right)\sin(\beta + \Delta\beta) - \left(\frac{l}{2} - a\right)\sin\beta\right] \tag{7}$$

Substituting the above formula into the crack strain energy release rate of the formulas (1), critical strain energy release rate can be calculated according to the crack propagation angle:

$$G = \frac{1}{b}\left(\frac{dU_e}{da} - \frac{dU_s}{da}\right) = \frac{1}{b}\left[\frac{1}{4}b\sigma_i\sin\beta - \frac{2M\sin\alpha_0}{l\cos(\beta - \alpha_0)}\right] \tag{8}$$

If internal parameter of formula is known, it can be approximated to the calculated strain energy release rate of the crack.

4 Cracking strain energy release rate calculation example

In order to verify the correctness of the former derivation, we need to determine the strain energy release rate of interface crack between the steel plate and the core. Literature [6] prefabricated interface crack by embedding PVC film before pouring the core. DCB experiment and SLB experiments are carried out to determine the critical strain energy release rate of I type crack for specimens with the soft hard core separately. The measured type I crack strain energy release rates are shown in table 2.

Table 2 Strain energy release rate of sandwich plate

Experiment name	The type of specimen	Energy release rate （N/m^{-1}）

Soft core	G_{I}^{c}	526
Hard core	G_{I}^{c}	1783

Combined with equation (8), at the beginning of propagation, $\beta = 0$, strain energy release rate can be calculate by the following formula:

$$G = \frac{2E_f I_f \theta}{bl\left(\frac{L_0}{2} - a\right)} \tan \alpha_0 \tag{9}$$

In which E_f is modulus of elasticity, I_f is moment on inertia of specimen; *b* is the width, L_0 is the actual length of specimen after large deflection; *l* is the gauge length; *a* is the crack length. When crack propagation angle α_0 and the critical strain energy release rate are determined, we can calculate the critical crack length based on the previous formulas. Since θ is a function of the bending load *Q* and the plastic rotation angle φ, through the analysis the formula can be obtained as followings:

$$\theta = \frac{Q\sqrt[4]{\frac{1}{4E_f I_f k^3}}}{\frac{l}{\cos\phi} - 2r} \tag{10}$$

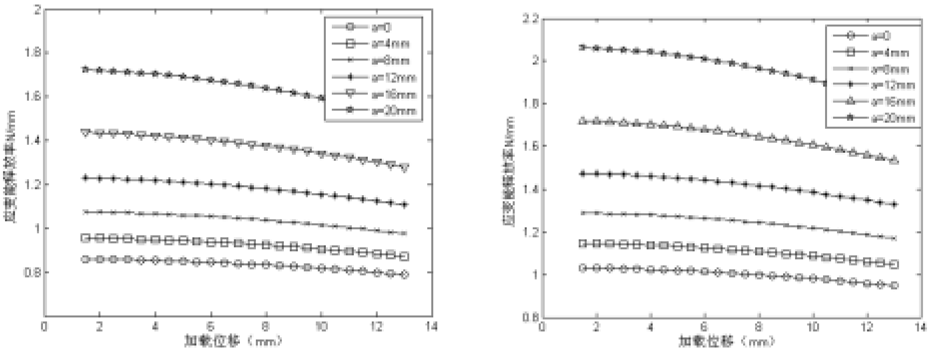
In which $k=k_0 b$, k_0 is foundation modulus; *r* is the radius of supported roll shaft. Bending load *Q* and the rotation angle φ can be obtained from fitting the experimental load-displacement curve. Based on the former three-points bending experiment, we fit the relationship by bilinear model:

Hard core: $Q = 1780 + (\lambda - 1.3)\tan 26.6°$

Soft core: $Q = 1480 + (\lambda - 1.3)\tan 16.0°$ (11)

In the formula, λ is loading displacement. Combined with the crack propagation angle α_0 determined from DCB and SLB experiments, the strain energy release rate corresponding to different crack lengths can be calculated, as shown in Figure 6.

From Figure 6, corresponding to different crack length values, strain energy release rate curve is substantially parallel, and slightly decreased. The larger the crack length is, the higher the strain energy release rates are. If strain energy release rate is larger than critical value, crack propagation occurs. Variation trend (Fig. 6b) of strain energy release rate with loading displacement is similar to Fig. 6a, the error is due to the ideal elastoplastic assumptions for faceplates material. Comparing the results of soft core and hard core, difference of strain energy release rate is not very large. The critical interface strain energy release rate of soft core and hard core is different, the hard core's critical strain energy release rate is 1.783N/mm, corresponding allowable critical crack length for specimen in this paper is 16mm; the soft core's critical strain energy release rate is 0.525 N/mm, which is less than the value of strain energy release rate at position *a=0*, This means that as long as specimen reach the yield limit, damage will be in the form of inter-layer cracking.



a Soft core specimen b Hard core specimen

Fig.6 Strain energy for different cores of specimen

5 Conclusion

Based on three-point bending experiments for sandwich plate with polyurethane elastomer core, it is found that specimens with different bond strength and core hardness have different failure modes. Here proposed a method of calculating the critical strain energy release rate to obtain the critical crack length values of different types of the specimen. Although there are some errors, but it can be substantially obtained the strain energy release rate and describe the propagation of interfacial crack.

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