EFFECT OF CROSS-SECTIONAL SIZE AND SHAPE ON THE FATIGUE RESISTANCE OF SEALED JOINTS TO SHEAR MOVEMENT

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Abstract
The effect of cross-sectional size and shape of polysulfide sealant beads on their shear fatigue resistance was studied experimentally and analytically. Nine types of rectangular sealing beads of different sizes and six types of concave shaped beads of different depths of concavity were repeatedly deformed by shear joint movement. Test results showed that the time to failure (cracking) was strongly influenced by the shape of the bead as opposed to the size of the bead. The crack initiation time was shorter for the beads with deeper concave shape. To investigate the reason for these results, the stresses in the beads were studied using a finite element method. It was concluded from both experimental and analytical results that a rectangular or slightly concave shape of the sealing bead provides the highest fatigue resistance to shear movement.

1. Introduction

Ensuring long term serviceability against joint movements is a matter of concern in designing sealed joints. A very important parameter affecting the longevity of sealed joints is their fatigue resistance. In the design process, fatigue resistance against both extension-contraction movement and shear movement needs to be considered. Fortunately, we have not had any severe earthquakes for several decades in Japan which would have been capable of inducing large shear joint movements and which might have resulted in shear failures of sealed joints. As a result, we have given little attention to the subject of shear fatigue of sealed joints.

However, the Hyougoken-Nanbu earthquake in 1995 made us realise the importance of shear fatigue resistance, since sealant beads were ruptured during the earthquake by shear movements in the joints. Besides the movement by earthquakes, wind also induces shear movements in the curtain wall joints of tall buildings. Considering that the number of such buildings is increasing, the performance of a sealant to shear joint movement will become more important in the future. These circumstances led us to initiate some basic studies on the shear fatigue of sealed joints in addition to the previously published, detailed papers on this subject [1-4].

In our study, we focused on the cross-sectional size and shape of sealant beads, which are the most important parameters in the design process, with the intent to clarify their effects on the shear fatigue resistance to sliding joint movement.

2. Shear fatigue tests of sealing beads of various sizes

2.1 Size of specimen

The effect of the size of sealant beads was studied for rectangular shapes, since these are considered the most basic design for sealed joints. Test specimens of nine cross-sectional sizes were prepared for the study as shown in Figure 1 by choosing the width and depth dimensions independently as 5 mm, 10 mm and 20 mm. Figure 2 shows a test specimen. A two-part polysulfide sealant was injected into the space between two aluminium bars of 280 mm length which were fixed at the specified joint width. A polyethylene film was installed at the bottom of the test joint as a bond breaker; the film was removed just prior to the fatigue testing. The specimens were cured for two weeks at room temperature and then stored in a chamber controlled at 50±2°C for two more weeks.

D \ W	5 mm	10 mm	20 mm
5 mm	D/W=1	D/W=0.5	D/W=0.25
10 mm	D/W=2	D/W=1	D/W=0.5
20 mm	D/W=4	D/W=2	D/W=1

Figure1: Cross-sectional size of rectangular specimen.

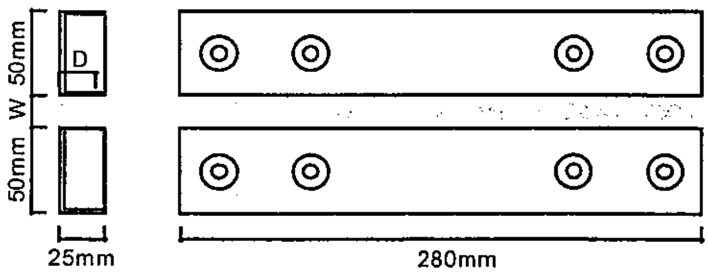


Figure 2: Test specimen (rectangular cross-section).

2.2 Fatigue test

For each cross-sectional size, two specimens were attached to the fatigue test equipment as shown in Figure 3. By placing the joints at two locations in the apparatus, they were subjected to repeated shear movements in the form of a sine curve with amplitudes of ± 60% and ± 100% of the joint widths and a period of 10 seconds. The surfaces of the specimens were periodically inspected by visual examination, using the naked eye for the top surface and a glass fibre scope for the bottom surface. The number of movement repetitions to crack initiation and the patterns of cracking were recorded. The fatigue tests were carried out at 20±2°C and were discontinued at one hundred thousand cycles unless any defects were observed in the sealant beads.

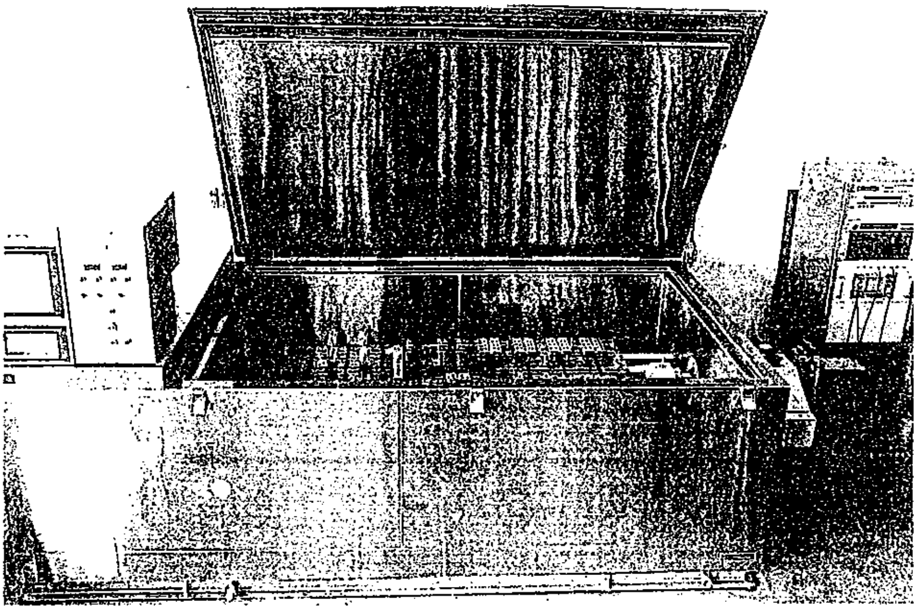


Figure 3: Fatigue test apparatus.

2.3 Test results and discussion

Cracks appeared in some specimens on their surfaces close to the aluminium support bars and developed along them by fatigue operation. Sealant beads are specified in the design process based on their shape factor which is defined as the ratio of depth (D) to width (W), D/W.

Figure 4 shows the relation between the number of cycles at crack initiation and the shape factor. The number of cycles at crack initiation is almost identical for all specimens at a given shear movement, regardless of their shape factors.

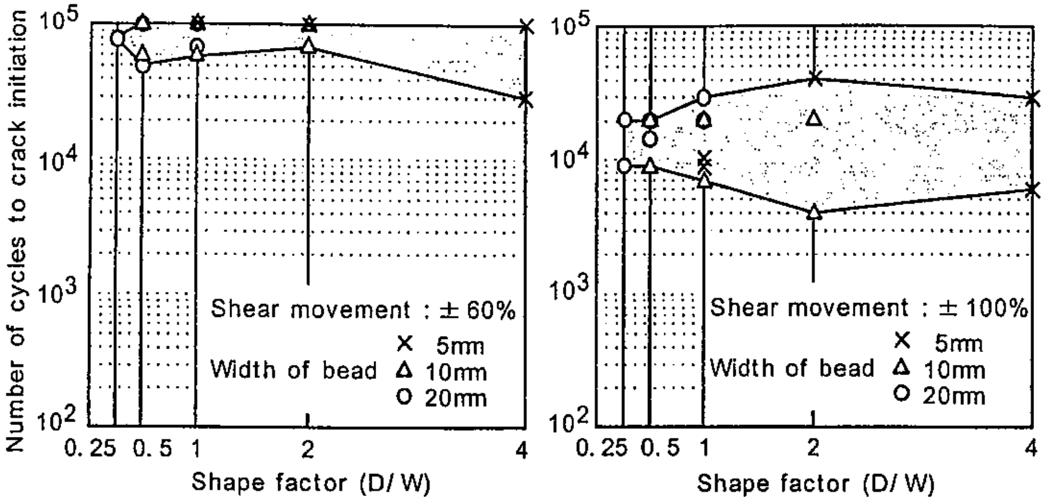


Figure 4: Relationship between number of cycles to crack initiation and shape factor.

3. Shear fatigue tests of sealing beads with various surface shapes

3.1 Surface shapes of sealing beads

Figure 5 shows a concave test specimen prepared for the study. Since in actual service joints, sealant beads having a width of 20 mm and a depth of 13 mm (shape factor, D/W, close to 2/3) were most frequently observed, we chose these measures as the minimum cross-section for the concave test specimens.

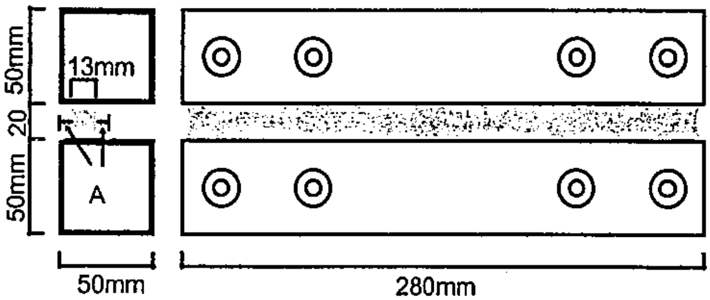


Figure 5: Test specimen (concave shape cross-section).

Concave test specimens were prepared with identically shaped top and bottom surfaces defined by the elliptic function $x^2/A^2 + y^2/(10\text{ mm})^2 = 1$, where A is the length of the semi-minor axis of the ellipse. In actual service joints, the shape of the top and bottom surface of the sealant bead typically differs. However, in order to simplify the experiments, specimens having the same shapes on both surfaces were prepared for the study. Six specimens with a depth in the concave surface ranging from 0 mm (a rectangular section bead) to 20 mm were prepared as shown in Figure 6.

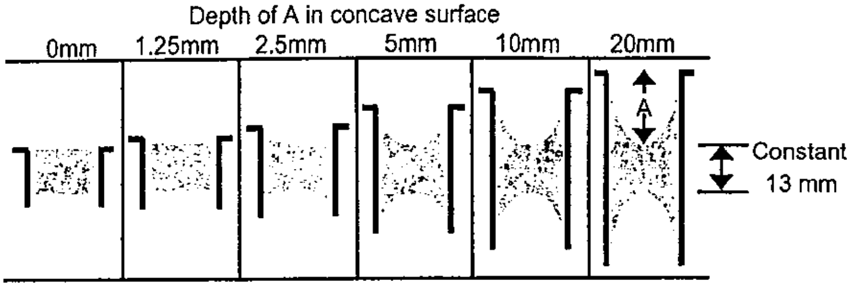


Figure 6: Cross-sectional shape of specimen.

3.2 Fatigue test

The fatigue test method used for concave test specimens was identical to the one described in the previous section, except that the tests were carried out at three amplitudes of movements, i.e. ± 60%, ± 80% and ± 100% of the joint width.

3.3 Test results and discussion

3.3.1 Cracking patterns

Fine cracks appeared on the surface of the specimens and gradually developed during the shear fatigue operation. Three kinds of cracking patterns due to shear movements were observed as shown in Figure 7; 'a': a crack starts first in a bead near to the substrate bars, 'b-1': a crack starts in the middle of the arc of a bead and develops in an X shape, and 'b-2': a crack starts also in the middle of the arc of a bead, but develops parallel to the substrate bars.

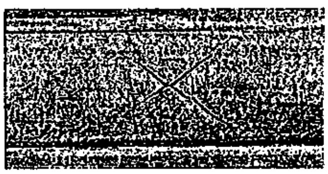
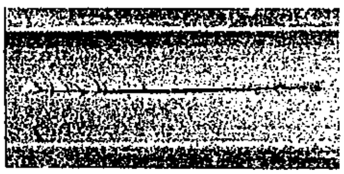
a	b-1	b-2
Parallel crack near substrate	X-shape crack in the middle of arc of bead	Parallel crack in the middle of arc of bead
		

Figure 7: Cracking patterns.

3.3.2 Influence of the depth of the concave surface shape on shear fatigue

Figure 8 shows the relationship between the number of shear movement cycles to crack initiation and the depth of the concave surface of the sealant beads. No cracks appeared on the surface of the specimens at the movement amplitude of ± 60%, therefore, the effect of the depth of the concave surface shape on shear resistance can not be discussed for this amplitude. As can be seen from Figure 8, the fatigue resistance clearly decreases for higher movement amplitudes (± 80% and ± 100%) and for higher depths (A) of the concave surface. However, no clear differences were observed between the test specimens with shallow concave surfaces.

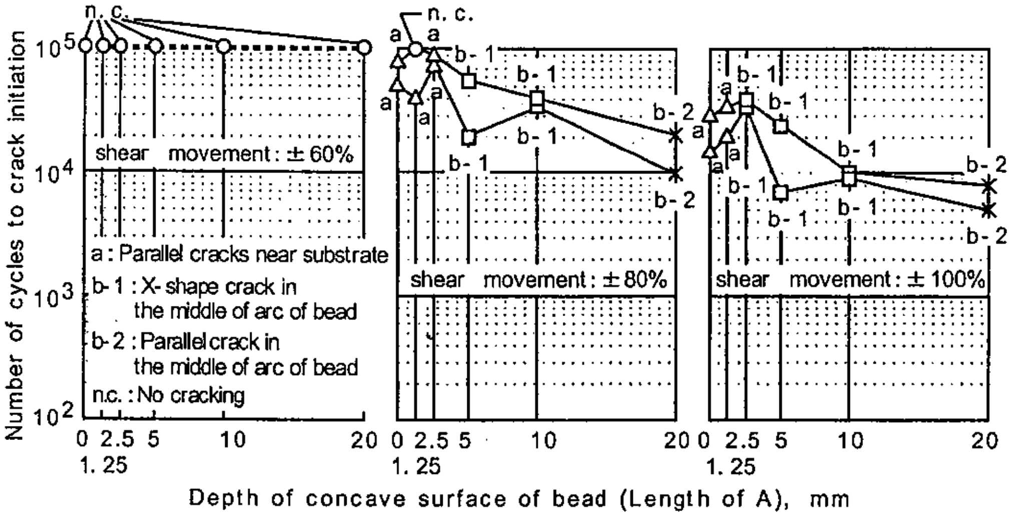


Figure 8: Relationship between depth of concave surface bead shapes (A) and number of cycles to crack initiation.

3.3.3 Relation between cracking patterns and depth of concave surface shape

The crack patterns are also indicated in Figure 8 (symbols a, b-1 and b-2). The 'a' type crack pattern was observed for beads with a straight surface or slightly concave surfaces. Crack pattern 'b-1' was observed for beads with moderate depths of the concave surfaces; while 'b-2' type cracking was observed for the bead with the deepest concave shape. The cracking pattern changes from 'a' to 'b-1' and finally to 'b-2' as the concave shape becomes deeper.

4. Stress in sealant bead being deformed in shear

The shear fatigue resistance of the sealant beads decreases and the cracking pattern changes as the concave shape deepens. It is obvious that these observations are a result of the stresses induced in the sealant beads. Hence, stresses and their distributions were studied using a finite-element-method (FEM) computer program.

4.1 Outline of analysis

In this study, a sealant bead was represented by a three-dimensional model as shown in Figure 9. An analysis of the accuracy of the calculation results led us to use models based on 120 elements. Calculations were carried out for six cross-sectional shapes with the depth of the concave surface being varied from 0 to 20 mm. Most sealants show viscoelastic behaviour in actual moving joints. However, the intent of this analysis was to determine the outline of the stress distribution induced in the beads by shear deformation. Therefore, a linear elastic analysis was carried out, using the simplified stress-strain relation shown in Figure 10 for the calculation.

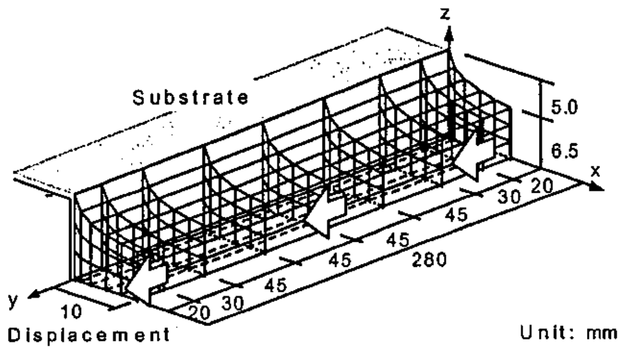


Figure 9: Analytic model (modelled is a quarter of the cross-section of the bead for the case of A = 5 mm).

4.2 Results and discussion

4.2.1 Tensile stress distribution in bead

Sealants are considered to be in a stretched state in the sheared joint; hence tensile stress is discussed here. Because of the edge effect, the stress in the area close to both edges of the sealant bead is generally higher than in the bulk of the specimen. Therefore, our analysis focused on an area in the middle of the specimen which is not influenced by the edge effect. This area can be determined by Saint-Venant's principle [5].

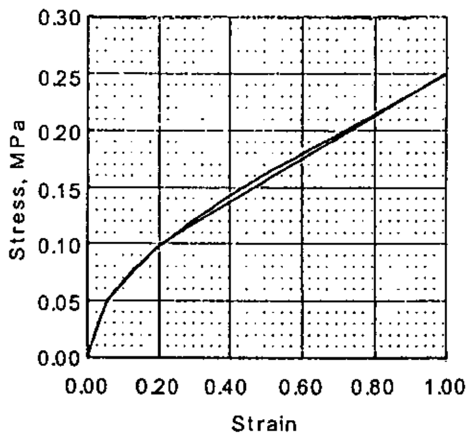


Figure 10: Stress-strain relation.

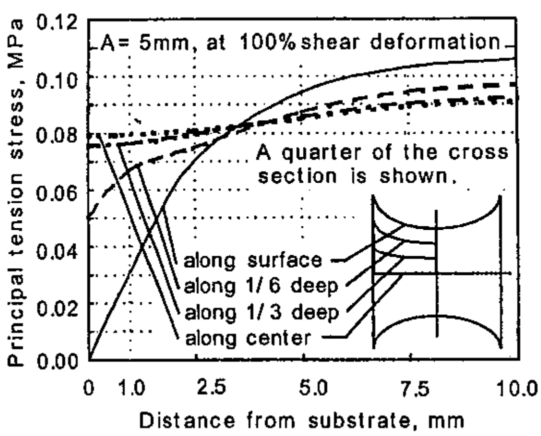


Figure 11: Distribution of principal tensile stress in the bead for the case of A = 5 mm.

Figure 11 shows the principal tensile stress distribution at four levels within the depth of the specimen with a concave depth of A = 5 mm. The variation of the stress along the x-axis (distance perpendicular to the substrate) is most noticeable at the surface of the bead, with the highest stress being reached in the centre of the concave sealant bead. For deeper levels within the sealant bead, the stress becomes less dependent on the x-axis.

4.2.2 Relation between stress and depth of concave surface shape

Figure 12 shows calculated principal tensile stress distributions along the bead surfaces at shear deformations of 60, 80 and 100%. The stresses are shown at the centre of the specimen length. The principal stress is independent of the x-axis (distance from substrate) for a rectangular shaped sealant bead. For sealant beads with concave surface shape, the stress in the area close to the substrate is lower than in the middle of the concave surface. The higher the concavity of the sealant bead, the further the stress concentration moves away from the substrates and the higher the stress level in the middle of the sealant bead.

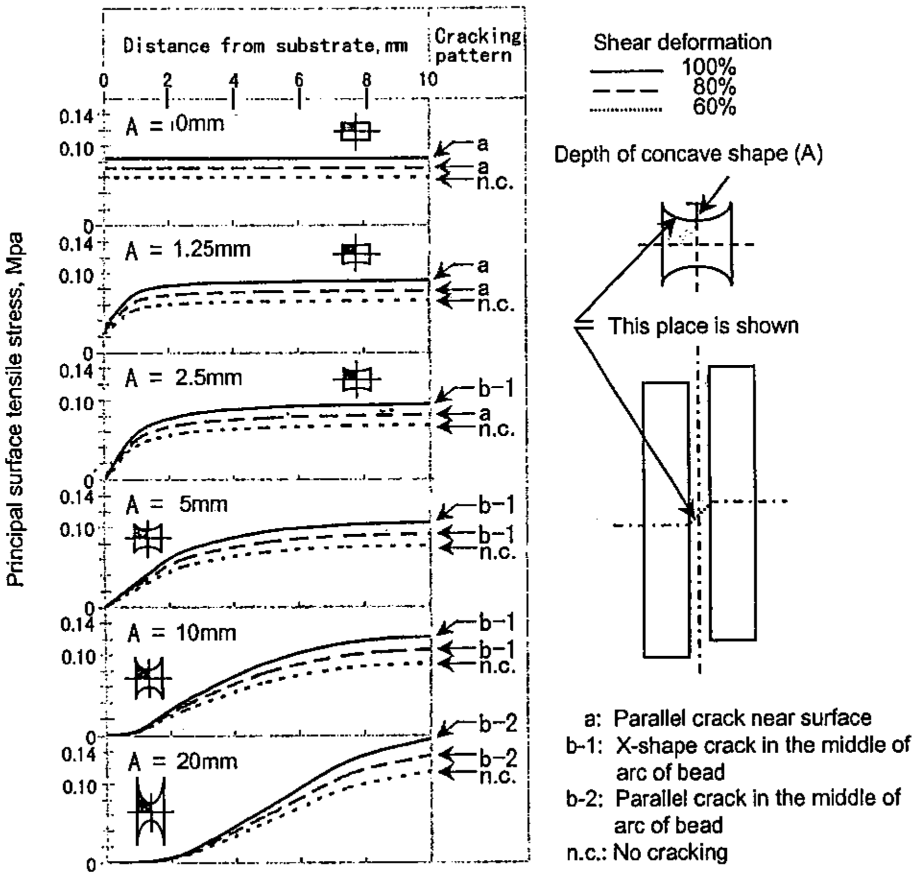


Figure 12: Distribution of principal surface tensile stress along bead surface for shear deformed specimens (stress at the centre of a specimen length is shown).

4.2.3 Relation between stress distribution and cracking pattern

The three crack patterns are indicated in Figure 12 by the same symbols as in Figure 7. They seem to be closely related to the stress distribution in the bead. The crack pattern 'a', a crack starting near the substrate and developing parallel to the substrate, is observed for beads with flat or slightly concave surfaces. This crack pattern may be induced by a stress gradient near the substrate surface resulting from the restraining effect of the substrates which is difficult to estimate by elastic analysis. The crack pattern 'b-1', a crack starting in the middle of a bead and developing in an X-shape, is observed for cross-sections with moderate concave surfaces such as 2.5 mm (at 100% shear movement), 5 mm or 10 mm deep. In these specimens, the highest stress is concentrated in an area several millimetres away from the substrate. The crack pattern 'b-2', a crack starting in the middle of a bead and developing parallel to the substrate, is only observed for the bead with the deepest concave surface (A = 20 mm). This crack pattern is caused by the stress in the middle of the concave surface which is much higher than in other areas of the sealant surface.

5. Cross-sectional shape of sealant bead with high resistance to shear fatigue

Finite-element-analysis showed that the shear fatigue resistance of sealant beads with a highly concave surface shape is inferior to that of rectangular or slightly concave shaped sealant beads, due to the high stress concentration in the middle of the sealant bead. Rectangular and slightly concave shaped sealant beads result in a more balanced stress distribution under shear movement and, therefore, one expects better fatigue resistance with these cross-sectional shapes. This finding is experimentally confirmed by shear fatigue testing results as shown in Figure 8. Therefore, rectangular or slightly concave sealant bead shapes are recommended as the most durable design for joints exposed to high shear movement.

6. Conclusion

The effect of cross-sectional sizes and shapes of polysulfide sealant beads on the fatigue resistance to shear joint movement was studied experimentally and analytically. The results obtained can be summarised as follows:

- The size of sealant beads does not have a clear effect on shear fatigue resistance for sealant beads having the same shape factor.
- The shape of the sealant bead has a much stronger effect on shear fatigue resistance; the deeper the depth of the concave shape, the lower the fatigue resistance.
- Rectangular or slightly concave shapes are considered durable cross-sectional designs for sealant beads exposed to shear movement.

7. Acknowledgement

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8. References

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