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# Determination of Crack Length in Polymeric Foam using Compliance Method

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***Abstract***

Compliance method is one of the most famous conventional methods for determining crack size during fatigue crack growth (FCG) test recommended by the ASTM standard. In the standard, the relationship between compliance and crack length was given and the compliance coefficients for computing crack length are suggested. However, the standard method was developed based on homogeneous metallic materials. Thus, the aim of this study is to verify the applicability of the standard coefficients for determination of crack length during fatigue crack growth test for polymeric material with cellular structure, i.e. polymeric foam. Compact tension (CT) specimen was prepared from PVC foam with the density of 130 kg/m$^3$. The fatigue crack growth test was performed at two different R-ratios of 0.1 and 0.4. Crack length was optically measured by a travelling microscope throughout the test. Comparing to the optical crack length, the compliance crack length determined using standard compliance coefficients recommended by the ASTM standard is found to underestimate the FCG rates. A new set of compliance coefficients was proposed here and resulted in a better correlation with the FCG curve from visual crack length.

***Keywords**:* compliance method, polymeric foam, crack propagation.

## 1. Introduction

PVC foam is widely used as a core material in sandwich structures which is applied in many applications such as wind turbine blades, marine structure, and light aircraft structure. During service the foam core in sandwich structure is at risk of fatigue fracture [1-3]. Thus, study of fatigue crack growth (FCG) in PVC foam core needs is necessary.

During the FCG test, precise measurement of crack length is required. In the ASTM E647 standard [4], various types of crack measurement method for metallic materials are recommended, e.g. optical method, compliance method, and electric potential method. However, for the PVC foam which is an electrically non-conductive material, the electric potential method is not applicable.

The most simple and inexpensive method is the optical method; yet, it is time consuming and needs accessibility to the specimen during the test. On the other hand, the compliance method, in which the change in material compliance is used to determine the propagation of crack, is

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less time-consuming. However, the measuring device needs to be carefully calibrated. Moreover, the method recommended in the ASTM standard is suggested only for linear elastic, isotropic, and homogeneous materials [5].

Many efforts have been made to apply the compliance method with polymeric materials. Fang et al. [7] studied fatigue crack growth in PC/ABS polymeric alloy and successfully applied standard compliance method to measure crack growth in their study. Varadarajan and Rimnac [6] investigated fatigue crack growth of ultrahigh molecular weight polyethylene (UHMWPE). The standard compliance method was unlikely applicable for the UHMWPE. However, they successfully developed the compliance method for the UHMWPE by applying a linear fit of the plot between normalized compliance and normalized crack length.

Calibrated compliance method was also developed to determine debonding fracture in foam-cored sandwich panels [8, 9]. However, development of the compliance method for determining crack growth in polymeric foam has not been done yet. Thus, the objective of the present work is to verify the applicability of compliance method for the PVC foam.

## 2. Experimental procedure

A cross-linked PVC foam (DIAB: Divinycell H130) was used in this study. SEM micrograph of PVC foam is shown in Fig. 1. The foam density is 130 kg/m$^3$, and its average cell size is 500 μm. In the previous work [10] the mechanical properties under tension were determined in accordance with ASTM D638 [11]. The tensile properties of H130 PVC foam are summarized in Table 1.

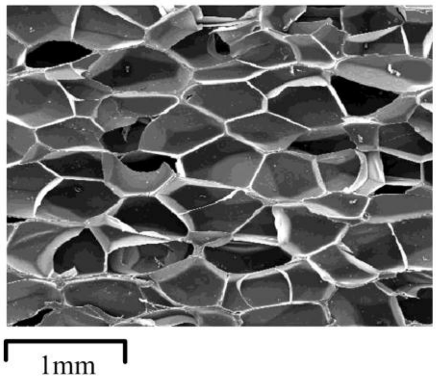


Fig. 1 Micrograph of H130 PVC foam.

Table. 1 Properties of H130 PVC foam [10].

| Properties | |
|---|---|
| Modulus, $E$ (MPa) | 76.82 |
| Poisson's ratio, $\nu$ | 0.3 |
| Yield strength, $\sigma_y$ (MPa) | 1.25 |

The compact-tension (CT) specimen was used in the present FCG test (Fig. 2). The foam CT specimens were cut from a 40-mm thick panel, machined to achieve a specimen thickness ($B$) of 30 mm. Preparation of the CT specimen was in accordance with ASTM E647 [4]. A notch was introduced by a table jig saw. Subsequently, a sharp precrack was introduced by a fresh razor blade. The FCG tests were carried out using a servo-hydraulic test machine (Instron 8872 with 5-kN load cell) at temperature of 25 ± 2 °C and relative humidity of 55 ± 5 %. A sinusoidal waveform with frequency of 5 Hz, and R-ratios of 0.1 and 0.4 were applied for the FCG tests. The crack length ($a$) was measured by a traveling microscope, while the load-line displacement ($\delta_{LL}$) was measured by an extensometer. Both traveling microscope and extensometer have precision of 10 μm.

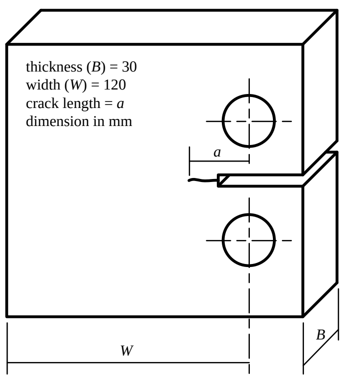


Fig. 2 Compact-tension (CT) specimen.

## 3. Results and discussion

### 3.1 Elastic compliance

The relationships between load ($P$) and load-line displacement ($\delta_{LL}$) during the FCG tests at both R-ratios of 0.1 and 0.4 are shown in Fig. 3 (a) and (b). As the load applied in the present FCG tests was low, the linear relationship between $P$ and $\delta_{LL}$ was observed.

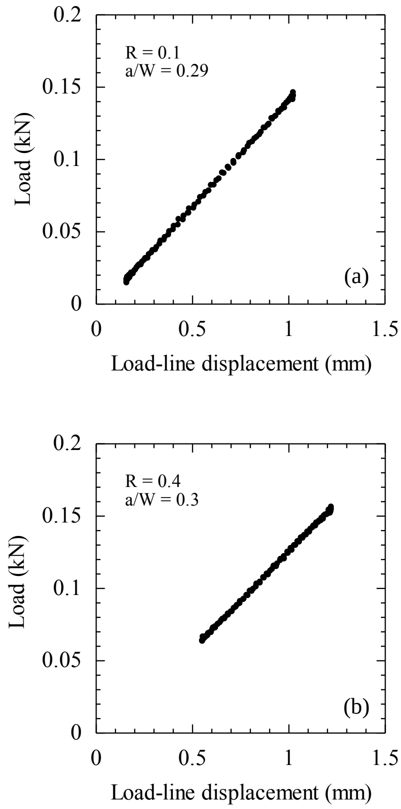


Fig. 3 Relationships between load and load-line displacement at R-ratios of (a) 0.1 and (b) 0.4.

According to the ASTM E647, compliance should be determined only from the linear part of the $P$ versus $\delta_{LL}$ curve [4], so the data closed to the reversal point of fatigue loading which is slightly nonlinear must be eliminated. The standard also suggests to consistently fit to either the loading data or the unloading data. Thus, in this study the unloading data with elimination of the data at the reversal point was used to determine compliance of the specimen. Fig. 4 is an example of an unloading curve from the test at R = 0.1 with the data elimination at reversal point. Compliance ($C$) can be determined from the slope of the curve as following,

$$\frac{1}{C} = \frac{\Delta P}{\Delta \delta_{LL}} \quad (1)$$

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where $\Delta P$ is the change in load and $\Delta\delta_{LL}$ is the change in load-line displacement of any given unloading data.

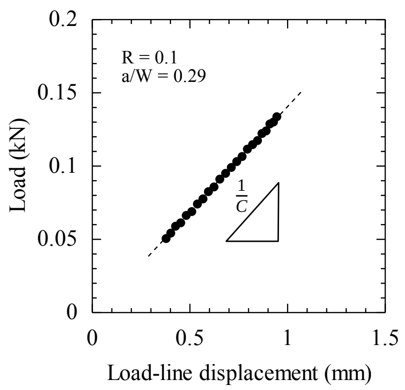


Fig. 4 Example of compliance determination from load vs. load-line displacement curve.

The relationships between compliance ($C$) and normalized crack length ($a/W$) for the test at R-ratio of 0.1 and 0.4 are illustrated in Fig. 5. As the crack length increased, deformation of the specimen increased, i.e. increasing of compliance. Moreover, for a given material and a given specimen geometry, compliance is unique and can be expressed as a function of crack length. Thus, the $C$ versus $a/W$ relationship was not influenced by the R-ratio.

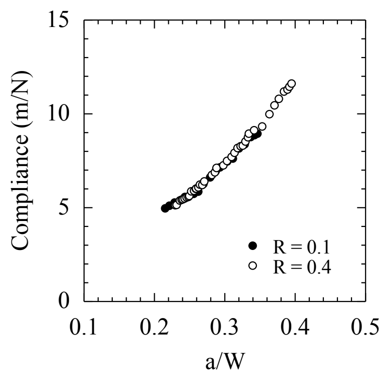


Fig. 5 Relationship between compliance and crack length at different R-ratios.

**3.2 Evaluation of compliance crack length**

For determination of crack length from compliance, the fifth-order polynomial function to describe the relationship between normalized crack length ($a/W$) and normalized compliance ($U_x$) are expressed as followings [4].

$$a/W = C_0 + C_1U_x + C_2U_x^2 + C_3U_x^3 + C_4U_x^4 + C_5U_x^5 \qquad (2)$$

$$U_x = \frac{1}{\left[\sqrt{ECB}+1\right]} \qquad (3)$$

where $E$ is the modulus, $C$ is the compliance determined from the $P$ versus $\delta_{LL}$ curve, and $B$ is the specimen thickness. The compliance coefficients $C_0$, $C_1$, $C_2$, $C_3$, $C_4$, and $C_5$ for CT specimen are given in Table. 2.

Table. 2 Standard compliance coefficients for CT specimen [4].

| $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ |
|---|---|---|---|---|---|
| 1.0002 | -4.0632 | 11.242 | -106.04 | 464.33 | -650.68 |

The ASTM standard also allows users to adjust the compliance crack length to match the optical crack length by using an effective modulus, $E'$ which is proportional to $E$, i.e. $E' = \gamma E$, where $\gamma$ is an adjustment factor [4]. However, to confirm the validity of the method, the effective modulus must not differ from the typical modulus by 10%. In this study, an effective modulus of 69.14 MPa was applied in the calculation to get the best correlation between the compliance and the optical methods.

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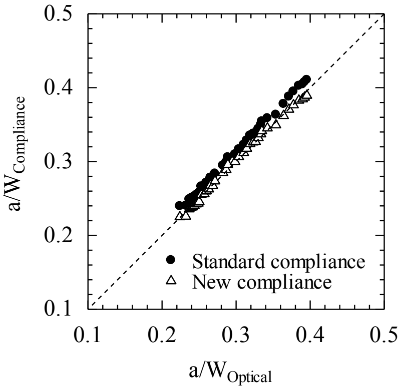


Fig. 6 Comparison between normalized crack lengths obtained from optical and compliance methods for the FCG test at R = 0.4.

The plot between normalized crack length obtained from the optical method and the compliance method using standard coefficients is illustrated in Fig. 6 as filled dots. Since the R-ratio did not influence the compliance, only the test data at R = 0.4 was represented here. The standard formula, Equation (2) is likely to overestimate the normalized crack length. The relatively high compliance crack length was possibly due to a very low modulus of the PVC foam, so that the specimen could encounter bending during loading. Moreover, during cyclic loading the rupture of cell walls at some distance ahead of the crack tip before the invisible growth of the main crack was possible [12, 13] and made the specimen more compliant.

To obtain compliance crack length for polymeric materials, Varadarajan and Rimnac [4] proposed a method to determine compliance calibration coefficients for UHMWPE by fitting the normalized compliance ($U_x$) plotted against the normalized crack length ($a/W$) using linear relationship. The linear fit was applied to the experimental data obtained in this study as shown in Fig. 7. Thus, $a/W = C_0 + C_1U_x$, where $C_0$ and $C_1$ are coefficients of the linear fit which are 0.8088 and -2.5864, respectively. The normalized crack length obtained from the new compliance coefficients was compared with the normalized crack length obtained optically (Fig. 6) and a better correspondence was observed. Noted that, technically, a fifth-order nonlinear fit, as recommended in the ASTM standard, is also possible in such case, as the differences between a linear fit and a nonlinear fit would not be much in the this region. However, it would increase the complexity of the calculation.

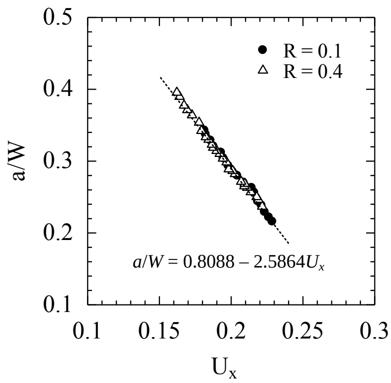


Fig. 7 Relationship between normalized compliance and normalized crack length at different R-ratios.

### 3.3 Determination of FCG curve

FCG curves obtained from optical and compliance crack lengths are illustrated in Fig. 8. For the FCG rate above $10^{-8}$ m/cycle, the FCG curves obtained from both standard and new compliance coefficients correlated well with the FCG curve obtained optically. However, for the FCG rate lower than $10^{-8}$ m/cycle, the new compliance method gave a better agreement with the optical measurement. While, the standard compliance method underestimated the FCG rates. Therefore, for the PVC foam, the standard compliance method should be carefully applied, particularly for the FCG rates in the near-threshold regime.

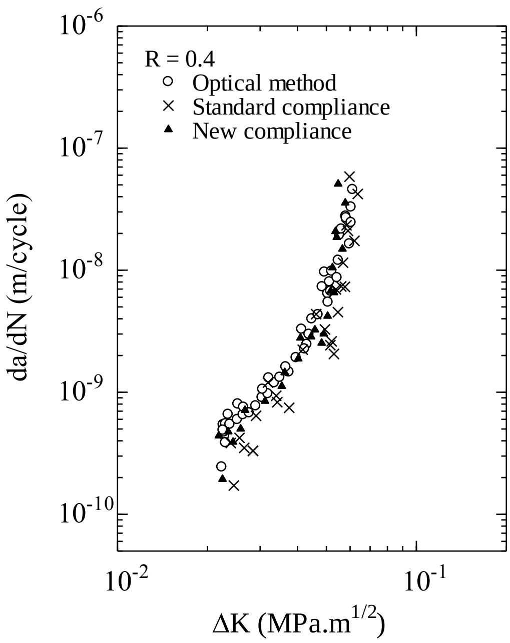


Fig. 8 FCG curve obtained from different crack determination methods at R = 0.4.

## 4. Conclusions

In the present work, the applicability of various compliance methods, e.g. standard compliance method and new compliance method, in order to determine crack during FCG test was studied. The findings are summarized as following.

1. The relationships between compliance versus normalized crack length obtained from the FCG tests at the R-ratios of 0.1 and 0.4 are similar, i.e. compliance was independent of R-ratio.

2. Due to the low stiffness of the PVC foam and the rupture of cell walls at some distance ahead of the crack tip before the invisible growth of the main crack, the standard compliance coefficients resulted in overestimated normalized crack length and underestimated FCG rates in the near-threshold regime.

3. As the experimentally based parameters, the new compliance coefficients obtained from a linear fit, is applicable for determination of FCG curve which gave a good correspondence with that obtained from the optical crack length. The method is moreover not complicated.

## 5. Acknowledgement

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