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Test Method

Experimental verification of yield strength of polymeric line contact structures

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ABSTRACT

Polymeric line contact structures are increasingly being used in engineering applications, so that the determination of the yield strength of the structures is of great importance. However, experimental investigation has shown that the current prediction of the yield strength in engineering provides conservative results relative to the actual yield behaviour of the structures. In the present study, a more accurate assessment for the yield strength of a line contact structure is proposed and, more importantly, this assessment was verified by a series of specially designed line contact tests based on optical full-field measurements. Specifically, the validity of this proposed assessment was examined by loading and unloading a polymeric line contact structure at different loading levels, and its accuracy was validated by singly loading line contact structures made from different polymeric materials until the occurrence of significant global plastic deformation. The experimental results confirmed that this proposed yield strength assessment enables accurate determination of the yield behaviour of line contact structures.

1. Introduction

Polymers are increasingly being used as structural materials in engineering applications owing to their diverse advantages such as ease of processing, high toughness, high strength-to-weight-ratio, etc. In some applications, the polymeric materials are used as contact structures such as rollers, gears and bearings [1–3]. For the safety and reliability of such structures, it is necessary to determine their load bearing capacity without permanent global deformation. Therefore, the assessment of the yield strength of contact structures becomes essential.

Currently, the assessment of the yield strength of a contact structure is based on the stress distribution in accordance with the Hertz contact theory. Taking a ductile line contact structure as an example, the maximum value of $\tau_{\max}$ (the maximum shear stress field) of the structure occurs at a point $0.78b$ below the surface of the cylinder, where b is the half contact width of the line contact structure, assumed to have a material Poisson's ratio of 0.3 [4]. According to the Tresca criterion, the yield would initially occur at this point when the maximum pressure at the contact interface reaches $1.67\sigma_s$, where σ_s is the yield strength of the material determined by uniaxial loading tests [4]. In the current engineering field, the contact structure is regarded to yield when a certain physical point in the structure initially yields; therefore, $1.67\sigma_s$ is often used as the yield strength of a line contact structure [5]. However, at the early stage of plastic flow, the yield zone is very small and surrounded by a large elastic zone, which is very similar to a small defect in the contact body. The global mechanical behaviour of the structure is not expected to be affected by this small yield zone [4–7]. In terms of this, the yield strength assessed based on $1.67\sigma_s$ tends to be conservative.

The Hertz theory also provides a global constitutive relationship between the average stress (defined as the distributed load over the contact area) and the equivalent strain (defined as the half contact width normalised to the radius of the cylinder). Ma et al. [8] investigated the yield zone evolution and its effect on the global behaviour of a line contact structure. In this previous study, it was found that the global mechanical behaviour of the line contact structure remained linear until the yield zone expanded onto the surface of contact bodies, even although the yield of the line contact structure already initially occurred inside since the maximum pressure at the contact interface reached $1.67\sigma_s$. This means that the maximum pressure when the global behaviour of the line contact structure becomes nonlinear should be higher than $1.67\sigma_s$,

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indicating that the predicted yield strength of the line contact structure in the current engineering field is conservative. Therefore, it becomes necessary to develop a more accurate yield strength assessment for line contact structures.

The objective of this study was to develop a new assessment for accurately determining the yield behaviour of ductile line contact structures and, more importantly, to experimentally verify the validity and accuracy of this new assessment using a series of specially designed line contact tests with different materials and loading conditions. In Section 2, the understanding of the yield mechanism of the line contact structure is briefly recalled, and a new yield strength assessment for the line contact structure is then derived. In Section 3, the detailed experimental procedures and results are presented. The concluding remarks are summarised in Section 4.

2. Yield strength of polymeric line contact structures

2.1. Yield mechanism of line contact structures

Fig. 1 shows a typical line contact structure consisting of a cylinder of radius *R* and a large thick plate. When the cylinder is loaded with a line-distributed load *P*, a rectangular contact area of width 2*b* is created. The Hertz contact theory provides the stress distribution and global constitutive relationship of such a structure. The stress distribution along the Z-axis of the cylinder during elastic deformation can be expressed as [4],

$$\begin{cases} \sigma_x = -2\nu P_0\left(1+\sqrt{1+\left(\frac{z}{b}\right)^2}-\frac{z}{b}\right) \\ \sigma_y = -P_0\left(\frac{1+2\left(\frac{z}{b}\right)^2}{\sqrt{1+\frac{z}{b}}}-\frac{2z}{b}\right) \\ \sigma_z = -P_0\frac{1}{\sqrt{1+z\left(\frac{z}{b}\right)^2}} \end{cases} \tag{1}$$

where ν represents the equivalent Poisson's ratio of the line contact structure, and P_0 is the maximum contact pressure over the contact interface during elastic deformation, given by Ref. [4],

$$P_0 = \sqrt{\frac{PE^*}{\pi R}} \tag{2}$$

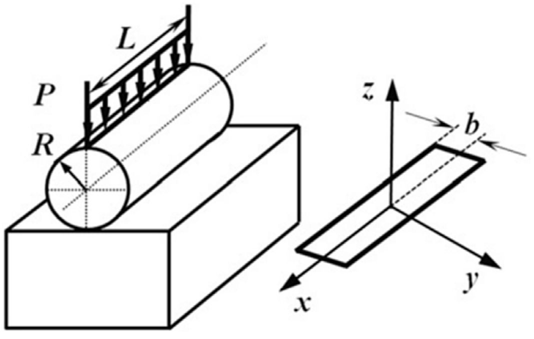

Fig. 1. Schematic of the line contact structure [8]. “Reproduced from *Polymer Testing*, Vol. 32, Ma et al., Experimental investigation of the yield process of a ductile polycarbonate cylinder subjected to line loading using digital image correlation, 461–467. Copyright (2013), with permission from Elsevier”.

where E^* is the equivalent Young's modulus of the line contact structure. Since σ_x, σ_y and σ_z in Eq. (1) are the principal stresses, it is possible to conclude that the point with the maximum $\tau_{\max}$ would yield when the maximum pressure over the contact interface reaches $1.67\sigma_s$ based on the Tresca criterion.

According to the Hertz theory, the global constitutive relationship of a line contact structure can be expressed as [4],

$$\sigma_{ave} = \frac{\pi E^*}{8}\varepsilon^* \tag{3}$$

where σ_{ave} is the average stress given by $\sigma_{ave} = P/2b$, and ε^* is the equivalent strain given by $\varepsilon^* = b/R$. Thus, Eq. (3) can be used as the linear elastic constitutive relationship of a line contact structure.

In the engineering field, a line contact structure is regarded to yield at the moment when $\tau_{\max}$ at the initial yield point exceeds the yield strength of the material. As explained earlier, however, the yield strength determined in this way is conservative. To accurately understand the yield behaviour of a line contact structure, Ma et al. [8] experimentally investigated the correspondence between the global constitutive relationship and the evolution of the yield zone of a polycarbonate (PC) line contact structure, as illustrated in Fig. 2. It was shown that the global relationship at Point C in Fig. 2a exhibits linearity when the yield zone (white area in Fig. 2b) initiates at the subsurface of the contact cylinder (Map c in Fig. 2b), and the global relationship at Point E in Fig. 2a remains linear until the yield zone expands onto the contact surface (Map e in Fig. 2b). After that the global relationship deviates from linearity. Similar to the yield definition of a material, the average stress level at the deflection moment of global relationship can be regarded as the yield strength of a line contact structure. Indeed, at the deflection moment, the contact interface undergoes a fundamental change. Before the deflection moment, the interface is purely elastic, but afterwards the contact interface is mixed elastic-plastic, as shown in Fig. 3. It is expected that the yield of a line contact structure can be attributed to this fundamental change.

Based on experimental investigation of the yield of a line contact structure [8], it is expected that the maximum pressure over the interface at the deflection moment of the global relationship should be higher than $1.67\sigma_s$. However, the expression of the maximum pressure at the deflection moment is unknown, and should be established. In the present work, the maximum pressure at the deflection moment is denoted by P_y. Due to nonlinear deformation, it is difficult to achieve an analytical solution of P_y. Therefore, in the present study, a finite element (FE) method was employed to establish the expression of P_y.

2.2. Yield strength assessment of line contact structures

During FE calculation, line contact structures (as illustrated in Fig. 1) with elastic-perfectly plastic and elastic-linearly hardening plastic constitutive material properties were loaded, and the deformation procedures were simulated. To obtain a general expression, line contact structures with different materials and dimensions were simulated. The detailed dimensions and material parameters are presented in Table 1. The length of all the line contact models is 50 mm. The simulations were performed in ABAQUS using element type CPE4R, namely, a four-node plane strain quadrilateral element, and a displacement loading mode. Considering the huge computational consumption and the nature of line contact, two-dimensional models of line contact structures were simulated. The mesh and boundary condition are shown in Fig. 4. The convergence of the mesh size in the FE calculation was confirmed in advance. The pressure distributions over the interface and contact widths were extracted from the FE simulation at the