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Material behaviour

Experimental investigation of the yielding process of a ductile polycarbonate cylinder subjected to line loading using digital image correlation

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ABSTRACT

The yielding formation and propagation of a ductile polycarbonate cylinder subjected to line loading, which corresponds to the global behavior of the structure, was experimentally studied and evaluated by measuring the strain fields on the end of the cylinder using Digital Image Correlation. The global behavior of the structure is expressed by a relationship between the average stress (load divided by contact area) and the equivalent strain (ratio of half width of contact area to radius of the cylinder); the contact area was measured in the same experiment by analyzing the images of the compressed pressure film captured through a transparent plate below the cylinder. A correspondence between the yielding state and the nonlinearity of the global behavior was constructed and, as loading was increased, the cylinder was found to first yield at a specific point after which a yielding core formed and propagated. Before the yielding core propagated to the surface of the cylinder, the global behavior of the structure remained linear, although the cylinder was no longer homogeneous and the material was nonlinear. After the yielding core propagated to the surface of the cylinder, the propagation was accelerated and the global behavior became nonlinear. The correspondence constructed in the paper will be helpful to understand the failure process and to evaluate the carrying capacity of a ductile polycarbonate cylinder subjected to line loading.

1. Introduction

Besides general applications as a functional material [1–3], polycarbonate (PC) is also used as a structural material in many modern day situations [4–8]. Among these are PC cylinders which are often subjected to line loading and frequently used in various engineering structures [9,10]. For engineering design, the deformation behavior, especially the yielding process of the PC cylinder, has been investigated in order to evaluate the carrying capacity of the cylinder. Theories in contact mechanics are often used to analyze the behavior of a cylinder subjected to line loading. Considering a ductile PC cylinder with a radius of R compressed on a plate, Hertz's elastic contact theory provides the expression of the stress distribution within the cylinder, and the width ($2b$) of the contact area between the cylinder and the plate [11]. It indicates that the maximum shear stress (τ_{max}) occurs at a point within the cylinder ($0.78b$ from the contact point). Thus, yielding first occurs at that point (termed the 'key point') according to the Tresca yielding criteria. In engineering design, the average stress corresponding to a given load when τ_{max} of the key point reaches the Tresca criteria of the material is regarded as the carrying capacity of the cylinder [12]. More and more points will yield and a yielding area will be formed if the loading increases continuously after the

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occurrence of the first yielding point. The evolution of the yielding area is difficult to analyze theoretically because the cylinder is no longer homogenous and the material behavior has become nonlinear.

In the elastic stage, Hertz's theory offers a linear relationship between the average stress (load divided by contact area) and the relative deformation b/R (known as the equivalent strain) to express the global mechanical behavior of the cylinder; this relationship could be regarded as constitutive of the structure. According to the analysis above, more and more points will yield and a small yielding area (known as the yielding core) around the key point will form as the load is increased. However, it could be expected that the yielding core will not significantly affect the global behavior of the structure when very small, such that the relationship between the average stress and the equivalent strain stays linear. When the yielding core grows large enough, the relationship becomes nonlinear. It should be noted that, however big the yielding core or whatever stage of yielding core development, the global behavior of the structure becomes nonlinear. To find this criterion, a correspondence between the developing of the yielding core and the loss of the linearity of the global behavior should be established. With this correspondence, the local yielding process could be clearly expressed by the global behavior of the structure, and also the principle of the entire global behavior of the cylinder will be clearly explained. Numerical studies [13,14] suggest that, when the yielding core grows to the surface of the structure, the global behavior begins to lose linearity. However, this correspondence has not been experimentally verified in existing literature.

Using a specially designed experiment, the contact area of the PC cylinder subjected to line loading was obtained, with the sectional deformation field obtained simultaneously. By analyzing the deformation field evolution measured by using Digital Image Correlation (DIC) [15,16], the initiation and evolution of the yielding core were observed. The yielding core evolution was then analyzed corresponding to the relationship between the average stress and the equivalent strain, and a clear correspondence between the yielding core evolution and the global behavior of the contact structure was established. Experiment results show that when the yielding core grows to the surface of the cylinder, the global behavior of the contact structure becomes nonlinear.

The experimental design and results are explained in section 2, the evolution of the yielding core is analyzed with respect to the global behavior of the structure in section 3 and, in section 4, the paper is concluded and some extensive problems are discussed.

2. Experiment and results

2.1. Mechanical behavior of a cylinder subjected to line loading

A cylinder subjected to line loading, as shown in Fig. 1a, can be analyzed using Hertz's contact theory. If the plate below the cylinder is made of the same material, then the maximum shear stress ($\tau_{\max}$) along the symmetry axis in the loading direction (z axis) is given as,

$$\tau_{\max} = \begin{cases} \dfrac{2}{\pi}\sigma_{ave}\left(2\nu\sqrt{1+\left(\dfrac{z}{b}\right)^2} - \dfrac{z}{b} - \dfrac{1}{\sqrt{1+\left(\dfrac{z}{b}\right)^2}}\right) & 0 \le \dfrac{z}{b} \le 0.436 \\ \dfrac{2}{\pi}\sigma_{ave}\left(\dfrac{1+2\left(\dfrac{z}{b}\right)^2}{\sqrt{1+\left(\dfrac{z}{b}\right)^2}} - 2\dfrac{z}{b} - \dfrac{1}{\sqrt{1+\left(\dfrac{z}{b}\right)^2}}\right) & 0.436 < \dfrac{z}{b} \end{cases}, \qquad (1)$$

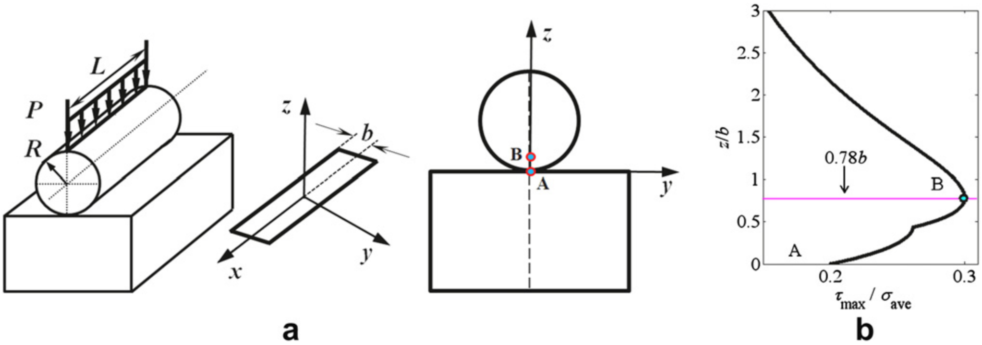

Fig. 1. An illustration of the stress variation of the cylinder subjected to line loading showing; (a) the model; (b) the stress distribution along loading direction.