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Elastic leak of a seal

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ABSTRACT

An elastomeric seal may leak by elastic deformation without any material damage. We describe elastic leak using a theoretical model, and watch a seal deform and leak using a transparent experimental setup. The elastomer seals the fluid by forming contact with surrounding hard materials. As the fluid pressure increases, the contact stress also increases but not as much. When the fluid pressure surpasses the contact stress, the elastomer and the hard materials lose contact in some region, forming a leaking path. The critical fluid pressure for elastic leak depends on the geometry and constraint of the seal, but is insensitive to the rate at which the fluid is injected. Our study points to the significance of elastic deformation in modes of failure that also involve material damage.

Seals are ubiquitous. Familiar examples are those in plumbing joints, drinking bottles, and pressure cookers. Engines require seals to enable gas-tight, reciprocating motion of pistons in cylinders [1]. Hydraulic fracture requires seals to isolate fluids in gaps between pipes and boreholes [2–5]. Seals, along with tires and bearings, are among the most significant applications of elastomers [6]. Seals are inexpensive, but their failure can be costly. The explosion of the space shuttle *Challenger*, for example, was traced to the failure of O-rings [7].

The softness of an elastomer is essential to both the function and failure of a seal. The elastomer seals a fluid in a gap between mating parts made of hard materials. The softness enables the seal to deform easily, adapting to unpredictable variations in its working environment, such as the height of the gap, the misalignment of the mating parts, the roughness of their surfaces, and changes in temperature. With this adaptation, neither the seal nor the mating parts need to be designed with high precision, which could be costly or impossible. The softness of the elastomer, however, also makes the seal prone to failure. The fluid pressure can cause the seal to deform and damage, leading to leak [1,8].

Here we study a particular mode of failure, elastic leak. An elastomer seals a fluid by forming contact with surrounding hard materials. As the fluid pressure increases, the contact stress also increases but not as much. When the fluid pressure surpasses the contact stress in some part of the contact region, the seal and the hard materials lose contact in this region, forming a leaking path which eventually penetrates through the whole contact region. This mode of failure is entirely due to elastic deformation: the seal leaks without any material damage. We construct a transparent experimental setup to watch the seal deform and leak, and compare experimental observations to theoretical predictions. We find that the critical fluid pressure for elastic leak depends on the geometry and constraint of the seal, but is insensitive to the rate at which the fluid is injected.

Whereas seals have been studied as boundary-value problems of elasticity (e.g., [9–11]), how the solutions of elasticity relate to the leak of seals is poorly understood. In

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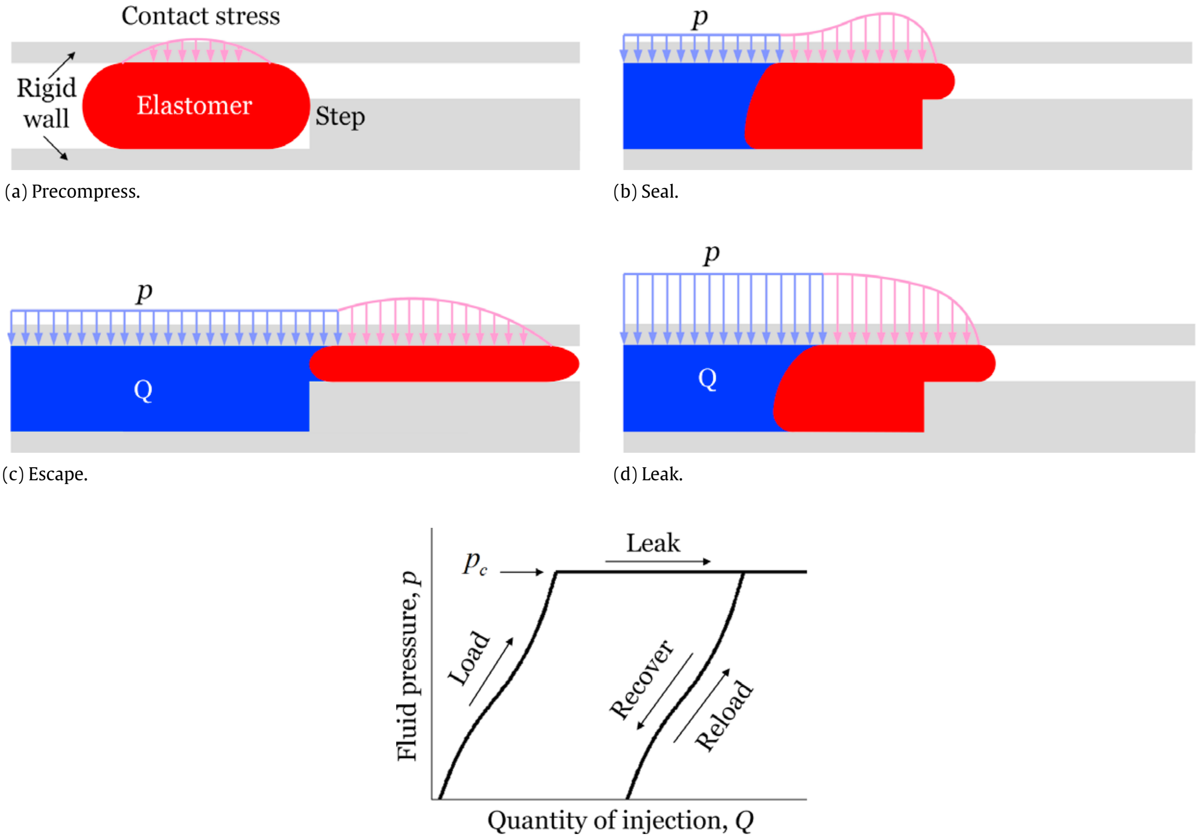

(a) Precompress.

(b) Seal.

(c) Escape.

(d) Leak.

(e).

Fig. 1. Elastic escape and elastic leak. (a) Prior to the injection of fluid, two rigid walls place an elastomer in a state of precompression. A step in the bottom wall defines the sealing site. Between the elastomer and the top wall is a distribution of contact stress. (b) When a fluid of quantity Q is injected, the fluid pressure p is applied on the elastomer and the elastomer deforms. The elastomer seals the gap when the contact stress rises above the fluid pressure. (c) The fluid pressure may cause the elastomer to squeeze into the tight space above the step, and escape from the sealing site. (d) The seal leaks when the contact stress in the interior of the contact drops below the fluid pressure. (e) A p–Q diagram that characterizes elastic leak.

postmortem examinations of failed seals, damage is often highly visible, but elastic deformation is not [8,12]. Perhaps because of this biased evidence, the central significance of elastic deformation to the leak of seals is underappreciated. The object of this paper is to quantify elastic leak using a combination of experiment and modeling.

1. A model of elastic leak

Prior to the injection of fluid, two rigid walls place an elastomer in a state of precompression (Fig. 1a). On the right side of the elastomer, a step in the bottom wall defines the sealing site. For the time being, we neglect the adhesion and friction between the walls and the elastomer, and assume that the elastomer deforms elastically without damage. The elastomer and the two walls form contact. We focus on the distribution of the contact stress between the elastomer and the top wall. The contact stress peaks in the interior of the contact, and vanishes at the edges of the contact [9].

When a fluid of a small pressure p is injected into the space on the left side of the seal, the elastomer deforms, pushes against the step, and extrudes a small part into the tight space above the step (Fig. 1b). The fluid pressure changes the region of contact, and increases and redistributes the contact stress [10,11]. When both the elastomer and the wall have smooth surfaces, the fluid pressure matches the contact stress at the edge of the contact. The edge of the contact would recede if the fluid pressure were above the contact stress at the edge of the contact, and would advance if the fluid pressure were below the contact stress at the edge of the contact. When the fluid pressure is low, the contact stress inside the contact rises above the fluid pressure. It is the rising contact stress in the interior of the contact that prevents the fluid from penetrating into the contact. The seal does not leak.

As the fluid pressure increases, the seal can fail in two modes. In one mode of failure, the whole elastomer squeezes into the tight space above the step, and escape from the sealing site [13] (Fig. 1c). Although the fluid pressure is still lower than the peak contact stress, the escaped seal is commonly considered a failure. This mode of failure, elastic escape, will not be studied in this paper. In the other mode of failure, as the fluid pressure increases, the peak contact stress also increases but not as much. When the fluid pressure reaches a critical value p_c, the contact stress peaks at the left edge of the contact and still matches the fluid pressure, whereas the contact stress in the interior of