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Elastic Leak for a Better Seal

Elastomeric seals are widely used to block fluids of high pressure. When multiple seals are installed in series and the spaces between the seals contain compressible fluids (e.g., gas or gas–liquid mixture), the seals often damage sequentially, one after another. Here, we demonstrate that the serial seals achieve high sealing capacity if individual seals undergo elastic leak, without material damage. When individual seals leak elastically, fluid fills the spaces between the seals. Instead of damage one after another, all the seals share the load. The elastic leak of individual seals greatly amplifies collective sealing capacity of serial seals. [DOI: 10.1115/1.4030660]

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Introduction

This paper studies the mechanics of elastomeric seals. We demonstrate the fundamental significance of elastic leak in achieving high sealing capacity. The findings will have direct impact on the design of seals for applications under extreme conditions, such as seals used in hydraulic fracture. Seals are among the most significant applications of elastomers. Elastomeric seals have the advantages such as large sealing range, low cost, light weight, and easy to manufacture. As a result, they are widely used in everyday life (e.g., plumbing joint, drinking bottle, and pressure cooker) and various industrial applications (e.g., engine, pressure pump, and packers).

We are particularly interested in the elastomeric seals (i.e., packers) used in oil and gas industry to block fluids of high pressure. Applications include water shut-off, inflow control, and multistage hydraulic fracture [1–5]. It is now widely appreciated that hydraulic fracture is principally responsible for the boom in shale gas exploitation [6]. The essential parts of a packer are one or more elastomeric elements (individual seals), bonded around a metallic pipe, and protected at the ends by metallic gauge rings (Figs. 1(*a*) and 1(*b*)). The elastomeric elements are either deformed by mechanical mechanisms [1] (e.g., mechanical packer), or swollen by imbibing fluids [7–9] (e.g., swellable packer). The elastomeric elements seal the gap between the pipe and the wellbore and prevent the fluid from flowing from a zone of high pressure to a zone of low pressure. The difference in the pressures between the zones is called the differential pressure. The maximum differential pressure that a packer can seal defines its sealing capability. With the increase of hydraulic pressure used in fracturing a reservoir, the sealing capability of packers also needs to be increased, i.e., the swellable packer needs to seal a differential pressure about 70 MPa during the fracture job [10]. (Recall that the elastic modulus of an elastomer is in the order of 1 MPa.)

To increase the sealing capability, one approach is to increase the length of elastomeric element, referred to as the continuous design (Fig. 1(*a*)) [4,11]. The other approach is to space several elements along the length, referred to as the spaced design (Fig. 1(*b*)). Relative to the continuous design, the spaced design has advantages such as low cost of manufacture, easy transport, and low risk for downhole operation. When the downhole fluid filled between elements is nearly incompressible, e.g., water, the differential pressure is distributed to each element. In that case, the spaced design is anticipated to seal larger differential pressure than the continuous design, since more gauge rings are used to constrain the deformation of elastomer. When the downhole fluid is highly compressible, e.g., nature gas or oil/gas mixture [12,13], external load may fail to transfer from the front element to subsequent elements. As a result, the elements are damaged

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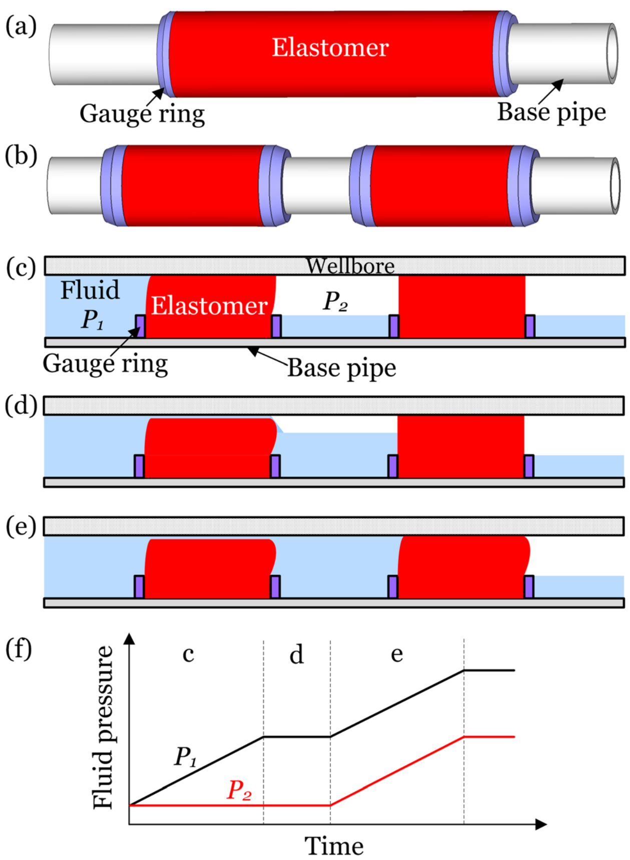

Fig. 1 Elastic leak of individual seals amplifies the collective sealing capacity of multiple seals. (*a*) Schematic of a continuous sealing design. (*b*) Schematic of a spaced sealing design. (*c*) After sealing, the spaces between sealing elements are partially filled with water. The first element deforms under the external pressure P_1, but the second element is nearly undeformed. (*d*) As P_1 reaches a critical value, the first element leaks elastically and the water fills the space between elements. (*e*) After water fully fills the space between the two elements, both elements deform and resist the differential pressure collectively. (*f*) The fluid pressures P_1 and P_2 as functions of time in the process (*c*)–(*e*).

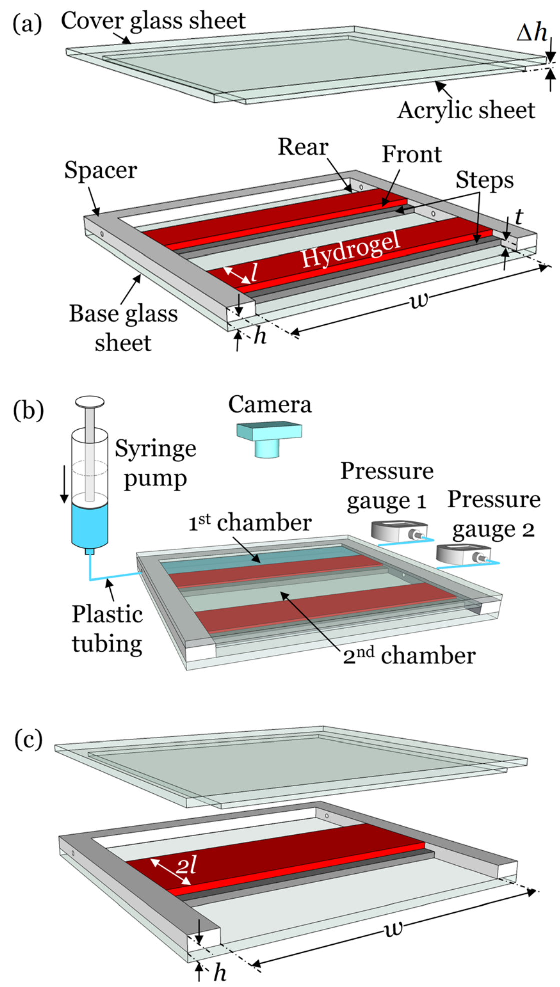

Fig. 2 Experimental setup. (*a*) Two blocks of a hydrogel, of dimensions *h*, *l*, and *w* in the undeformed state, are glued to a sheet of glass and to an acrylic spacer. Two acrylic steps with height *t* are glued to the base glass sheet and in contact with the front side of hydrogel blocks. An acrylic sheet of thickness Δ*h* is attached to the cover glass sheet. (*b*) When the cover glass sheet is glued to the spacer, the hydrogel is precompressed with a displacement Δ*h*. The glass, spacer, and hydrogels define two closed chambers. The first chamber connects to a syringe pump and a pressure gauge, and the second chamber connects to another pressure gauge. (*c*) For comparison, in the other setup, a hydrogel of dimensions *h*, 2*l*, and *w* in the undeformed state, is used.

sequentially. For example, Nijhof et al. [10] observed that with two swellable packers spaced along the pipeline, the differential pressure is mainly applied on the first element. When the differential pressure reached a critical value, the two elements were damaged one by one.

We have recently described elastic leak, a mode of leak that is caused by elastic (recoverable) deformation and without material damage [14]. Here, we show that elastic leak is essential for the spaced design to achieve high sealing capacity when fluid in the spaces between them is compressible (Figs. 1(*c*)–1(*f*)). Initially, the space between the two sealing elements is filled with water/air mixture (Fig. 1(*c*)). With the increasing of the external pressure P_1, the pressure in the middle chamber P_2 is nearly unchanged, because the initial change of pressure in air is negligible (Fig. 1(*f*)). The external load is mainly applied on the first element, which deforms. The second element, however, is nearly undeformed. When the differential pressure, P_1–P_2, reaches a critical value, the first element loses the contact with wellbore in some regions, forming a very thin leaking path (Fig. 1(*d*)). This leak, which we call elastic leak, is due to the elastic deformation of the elastomer and no material damage is involved. With water fully filling the middle region, differential pressure becomes evenly distributed to the two elements (Fig. 1(*e*)). As a result, P_2 increases in association with the increase of P_1 (Fig. 1(*f*)). These two spaced elements remain sealing until the fluid pressure P_1 reaches a higher critical value (Fig. 1(*f*)). With more elements spaced along the pipeline, the critical leaking pressure will be higher. In addition, the leaking path can be sealed whenever P_1 drops below the critical value since elastic leak is reversible. In contrast, P_2 will be identical to P_1 after the damage of the first element if the leak is due to material damage. Then the elements will fail sequentially, and the critical leaking pressure cannot be increased by increasing the number of elements.

In this work, we modify a desktop experimental setup introduced in our previous work [14] to demonstrate that the spaced design seals larger fluid pressure than continuous design. We further show that when air (highly compressible) filled between elements, spaced sealing design is functional when elements leak elastically, and fails when elements leak due to material damage.

Experiment

Our experimental setup uses a hydrogel as the sealing element (Fig. 2). The low elastic modulus of the hydrogel allows us to

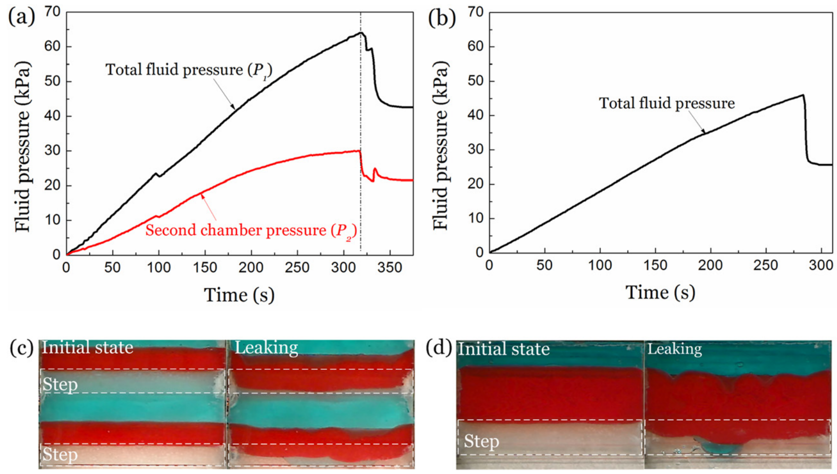

Fig. 3 Comparison between spaced and continuous sealing designs. In the spaced sealing design, two hydrogels (crosslinker (wt.%) = 0.06% and water (wt.%) = 88%) with dimensions of $l = 15.00$ mm, $h = 6.00$ mm, and $w = 120.00$ mm, is precompressed with a displacement $\Delta h = 0.80$ mm, i.e., $\varepsilon = 13.3\%$. The height of the steps $t = 2.60$ mm. The two chambers are filled with water before loading. The syringe pump injects water at a constant rate of 2 ml/min until the seals leak steadily. In the continuous design, all the conditions are identical to spaced design except the sealing element becomes a continuous block with the dimensions $2l \times h \times w$. (*a*) The fluid pressures as functions of time for spaced design. (*b*) The fluid pressure as a function of time for continuous design. (*c*) and (*d*) show the snapshots of the seals at the unpressurized state and leaking state corresponding to (*a*) and (*b*), respectively.

perform the experiments at relatively low fluid pressure, on desktop. The transparency of the setup allows us to watch deformation, leak and recovery in situ. We synthesize polyacrylamide hydrogel using the free-radical method [14]. Two identical blocks of the hydrogel, of the dimensions l, w, and h in the undeformed state, are glued parallel to a glass sheet and an acrylic spacer (Fig. 2(*a*)). We use acrylic steps with the height t to represent the effect of gauge rings and constrain the extrusion of sealing elements. Two steps are glued to the base glass sheet and in contact with the front side of hydrogel blocks. A transparent acrylic sheet of thickness Δh and width w is glued to the cover glass sheet. When the cover glass sheet is glued on the top of the spacer, the hydrogel is compressed with a strain $\varepsilon = \Delta h / h$ (Fig. 2(*b*)). No adhesive is applied between the cover glass sheet and hydrogel. The glass, spacer, and hydrogels form two closed chambers. We use a syringe pump to inject water into the first chamber at a constant rate and measure the pressures in the first and second chambers using two separate pressure gauges. The second chamber is either filled with water or air to mimic nearly incompressible or highly compressible downhole fluid. A digital camera is used to monitor the movement of hydrogels (colored red) and water (colored blue). For comparison, we also replace two sealing elements in this setup with one sealing element with the dimensions $2l$, w, and h (Fig. 2(*c*)).

Results and Discussion

First, we compare spaced and continuous sealing designs for an identical total length of sealing elements. In this case, water as a representative nearly incompressible fluid is fully filled in regions between two sealing elements before loading. Associated with the syringe pump injecting water into the first chamber, the fluid pressure measured by gauges in spaced and continuous designs are plotted in Figs. 3(*a*) and 3(*b*), respectively, and the snapshots for elements deforming and leaking are plotted in Figs. 3(*c*) and 3(*d*), respectively. With water filled between elements, the fluid pressures in the first and second chamber, P_1 and P_2, respectively, increase simultaneously (Fig. 3(*a*)), which indicates that the external load is distributed to both sealing elements. When P_1 reaches 64 kPa and P_2 reaches 30 kPa, both elements leak (Fig. 3(*c*)). This observation demonstrates that both elements leak at the same differential pressure about 30 kPa. For comparison, we measure the leak pressure of one continuous sealing element with the length doubled and other dimensions identical to the spaced sealing element (Figs. 3(*b*) and 3(*d*)). With the same total length, this

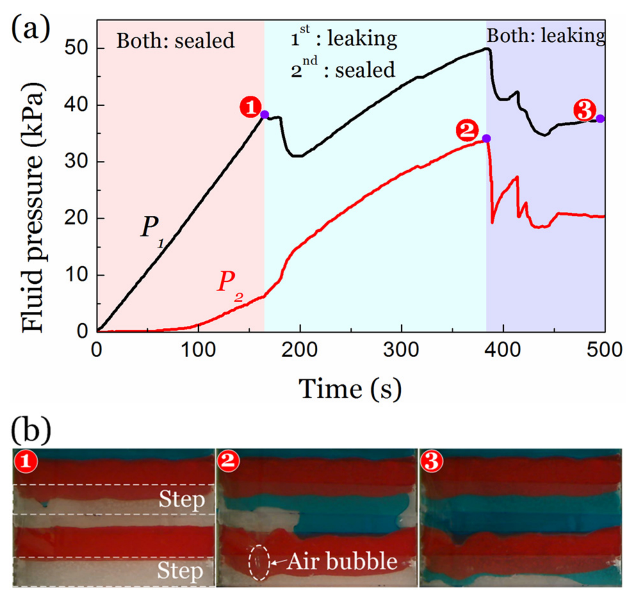

Fig. 4 Spaced sealing design with air filled between elements before loading. Two blocks of a hydrogel with the identical dimensions to the previous test are precompressed with a displacement of $\Delta h = 0.75$ mm, i.e., $\varepsilon = 12.5\%$. The height of steps $t = 2.57$ mm. The syringe pump injects water at a constant rate of 2 ml/min. (*a*) The fluid pressures in the first and second chambers as functions of time. (*b*) Three snapshots of the seals corresponding to the states marked in the pressure–time curves in (*a*).

continuous block leaks at 46 kPa, about 30% lower than the spaced design (Fig. 3(*b*)). This difference is due to the extra step used in spaced design that can constrain the deformation of elastomer element.

Next, we show that elastic leak enables the spaced sealing design to function even when fluid filled between elements is highly compressible. We trap air in the second chamber initially. With the increase of P_1, P_2 is nearly zero at the beginning and slightly increased, which is caused by the compression of air in the second chamber (Fig. 4(*a*)). As a result, the first element undergoes large deformation while the second element is nearly undeformed (snapshot 1 in Fig. 4(*b*)). Without water filled between elements, the external load cannot be evenly distributed among elements. When P_1 reaches 38.3 kPa, the first element leaks elastically while the second element still seals (Fig. 4(*a*)). With more water filled in the second chamber, the external load has distributed to two sealing elements, i.e., the increase of P_2 is proportional to the increase of P_1 (Fig. 4(*a*)) and both sealing elements deform in this stage (snapshot 2 in Fig. 4(*b*)). A nearly constant pressure difference between P_1 and P_2 is observed in this stage. This is consistent with our previous observations [14] that upon elastic leak, the differential pressure applied on the elastomer is nearly a constant. In other words, the first element can carry a certain amount of differential pressure while the element is leaking. This behavior differentiates elastic leak and damaged leak. When P_1 increases to critical pressure 49.9 kPa, both elements leak. Both P_1 and P_2 reach a plateau after a precipitous drop (Fig. 4(*a*)). The trapped air is expelled and replaced by injected water (snapshot 3 in Fig. 4(*b*)).

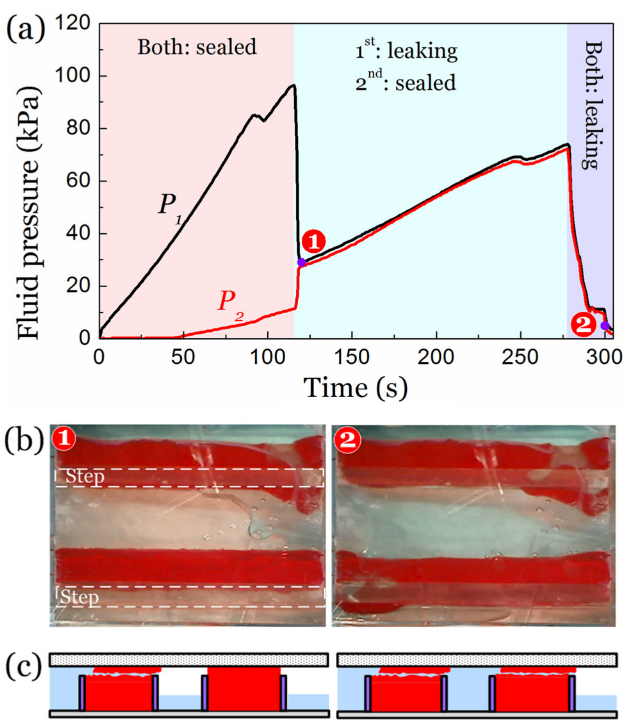

Fig. 5 The spaced hydrogels fail sequentially by material damage. Two blocks of a hydrogel (crosslinker (wt. %) = 0.3%, water (wt. %) = 92%) with dimensions of h = 6.00 mm, l = 15.00 mm, and w = 120.00 mm, are precompressed with a displacement Δh = 1.50 mm, i.e., $\varepsilon = 25\%$. The height of steps t = 3.00 mm. The syringe pump injects water at a constant rate of 5 ml/min until both the hydrogels fail. The high concentration of crosslinks makes the hydrogel brittle, so that the individual seal leaks by forming cracks. (*a*) The fluid pressures in the first and second chambers as a function of time. (*b*) Two snapshots of the seals corresponding to states marked in the pressure–time curves in (*a*). (*c*) Schematic of sequential failing of spaced seals by material damage.

These experimental results broadly confirm the mechanism illustrated in Fig. 1. The difference between experiments and simplified mechanism is due to the effect of air pressure change in the second chamber, which is neglected in the idealized analysis. The fluid pressure applied on the first chamber is on the same order of magnitude of air pressure since the hydrogel blocks used in this experiment is relatively soft. Therefore, the effect of air pressure is non-negligible. We anticipate the effect of air pressure will be less significant when elastomer is stiffer, e.g., the modulus for elastomer used in real application is on the order of 1–10 MPa. The corresponding pressure–time curve will be closer to Fig. 1(*f*).

For comparison, we change the material of sealing element to be a relatively brittle hydrogel to study the consequence of damaged leak. In this mode of leak, the seal suffers material damage and does not regain sealing capacity after leak. The second chamber is set to be empty of water before loading. The pressure–time curve for the first stage, where both elements seal, is similar to Fig. 4(*a*). Because the hydrogel is brittle, the seal leaks by forming a crack (snapshot 1 in Fig. 5(*b*)). After this damaged leak, the seal cannot sustain any differential pressure, i.e., P_1 and P_2 are nearly identical after the first element leaks (Fig. 5(*a*)). Consequently, the fluid pressure is entirely applied on the second element, which fails subsequently (snapshot 2 in Fig. 5(*b*)). Consequently, if individual seals suffer damaged leak, the critical leaking pressure cannot be increased by increasing the number of sealing elements. Our experiments demonstrate the central significance of elastic leak to achieving high sealing capacity of the spaced design.

Conclusion

We use a desktop experimental setup to observe seals to deform and leak and compare the spaced and continuous design. We find that with water between elements, spaced design can seal larger differential pressure than continuous design. We also study the case when air is filled between spaced elements before loading. We find that elastic leak enables the differential pressure to distribute to two spaced elements. By contrast, when seals leak by material damage, the differential pressure cannot be distributed and elements are damaged sequentially. The elastic leak of individual seals amplifies collective sealing capability of serial seals.

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