Chapter

Swelling Elastomers and Tubular Expansion—Numerical Investigation

Sayyad Zahid Qamar, Maaz Akhtar and Tasneem Pervez

Although this may seem a paradox, all exact science is dominated by the idea of approximation. When a man tells you that he knows the exact truth about anything, you are safe in inferring that he is an inexact man.

Bertrand Russell

Abstract

Swell packers were initially used for repair of old and damaged wells, but they are now increasingly used for higher productivity and profitability through developments like slim well design and reduced-cement or cementless completions. Solid expandable tubular (SET) technology has gained popularity in the petroleum development industry as it can reduce well costs and improve well performance. A conical mandrel is pushed or pulled through a petroleum tubular, either hydraulically or mechanically, to expand it (in-situ) to the desired diameter. In SET applications such as water shutoff and zonal isolation, swelling elastomers are an obvious choice as a sealing material. For proper downhole deployment of swell packers in SET applications, it is important to have a good idea about their behavior under a given set of field conditions. Design and manufacturing of SET applications using swelling elastomers as sealing elements also needs some sort of seal performance analysis.

Keywords: solid tubular expansion, swell packers, seal performance, finite element analysis

1. Introduction

Swell packers were initially used for repair of old and damaged wells, but they are now increasingly used for higher productivity and profitability through developments like slim well design [1] and reduced-cement or cementless completions [2]. Solid expandable tubular (SET) technology has gained popularity in the petroleum development industry as it can reduce well costs and improve well performance [3, 4]. A conical mandrel is pushed or pulled through a petroleum tubular, either hydraulically or mechanically, to expand it (in-situ) to the desired diameter [5–7]. In SET applications such as water shutoff and zonal isolation, swelling elastomers are an obvious choice as a sealing material [8, 9]. For proper downhole deployment of swell packers in SET applications, it is important to have a good idea about their behavior under a given set of field conditions [10]. Design and manufacturing of SET applications using swelling elastomers as sealing elements also needs some sort of seal performance analysis.

Schematic layout of tubular expansion against rock formation or outer steel casing, together with swelling elastomer seals, is shown in **Figure 1**. Compression of elastomer against the formation provides the required sealing [11]. This compression can be achieved through expansion of the inner tubular, by swelling of the elastomer element against the formation [12], or through a combination of the two. In the usual case, when one end of the SET is anchored and the other is free, the expansion process is known as fixed-free. In the rare occurrence when both ends are fixed, due to some aberrations in the expansion process (such as sticking of the tubular to the formation at some point), the condition is termed as fixed-fixed.

This chapter reports results of numerical (finite element) simulation used to investigate the effect of various field conditions on the sealing or contact pressure generated between the elastomer element and the rock formation [13]. This is the first study of its kind, investigating seal behavior based on material properties of expandable tubular and different swelling elastomers used in actual oil wells. These parameters include elastomer seal material, seal thickness, SET expansion ratio, elastomer compression ratio, formation type (rigid, elastic, elastic-plastic), and SET boundary conditions (fixed-free or fixed-fixed). Results of this work could be used by field engineers, application developers, and researchers for performance analysis and design improvement of solid expandable tubulars and swelling elastomer applications, and for proper selection of packers for a given set of field conditions.

1.1 Elastomer seal material

Various swelling elastomers have been developed to suit different types of well conditions (water salinity, temperature, differential pressure, etc). Choice of elastomeric material will definitely have an impact on seal performance. Based on experimental studies conducted by the authors on material characterization of

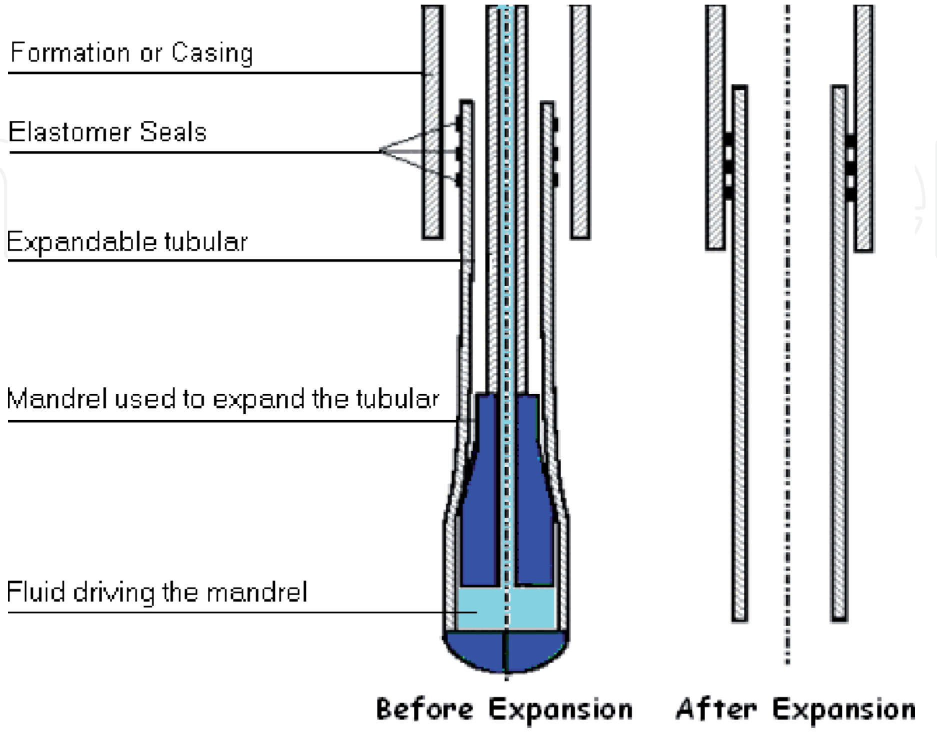

Figure 1.
Schematic illustration of tubular expansion with swelling elastomer seals.

swelling elastomers used in the regional oil fields [14, 15], five elastomer materials are used in this study. These seal materials are referred to as elastomer-1 (E1), elastomer-2 (E2), etc. Average values from three samples of each elastomer are used as input for the numerical model. A typical three-sample stress-strain curve for one of the elastomers is shown in **Figure 2**. Averaging out the three curves for each elastomer, **Figure 3** shows the representative stress-strain behavior for the five elastomer materials used in the study.

1.2 Expansion ratio (*ER*) and compression ratio (*CR*)

By using mandrels of different size, different expansion ratios can be achieved for a tubular of the same initial diameter [16]. Expansion ratio (*ER*) describes the percentage increase in tube diameter due to the expansion process

$$ER = \frac{OD_m - ID_t}{ID_t} * 100. \quad (1)$$

OD_m is the outer diameter of the mandrel (cone), and ID_t is the inner diameter of the pre-expanded tubular (SET). More important in terms of the seal contact pressure generated is the elastomer compression ratio (*CR*) that describes the amount of compression of the seal. This is the combined effect of expansion of the steel tubular, and swelling of the elastomer seal when exposed to a swelling medium.

$$CR = \frac{ER * R_t - G}{t} * 100. \quad (2)$$

This can also be expressed in terms of the amount of expansion of the tubular as

$$CR = \frac{(OR_m - IR_t) - G}{t} * 100. \quad (3)$$

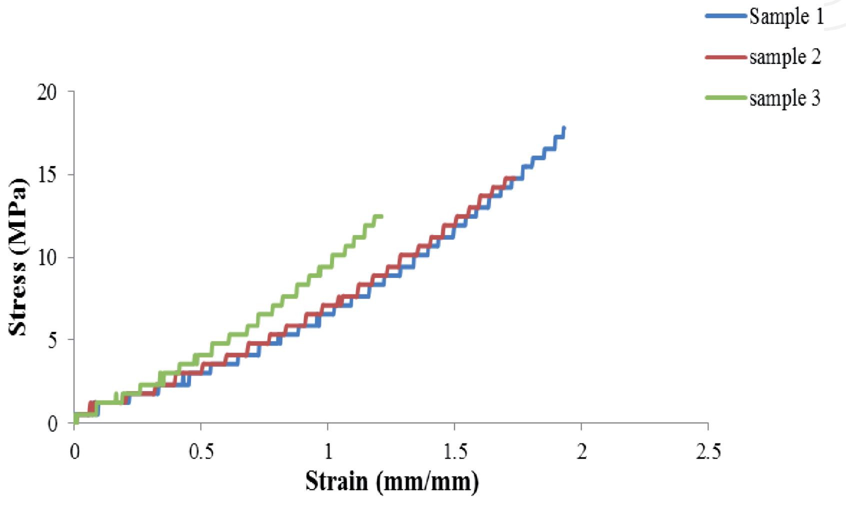

Figure 2.
Three-sample stress-strain graph for elastomer-3.

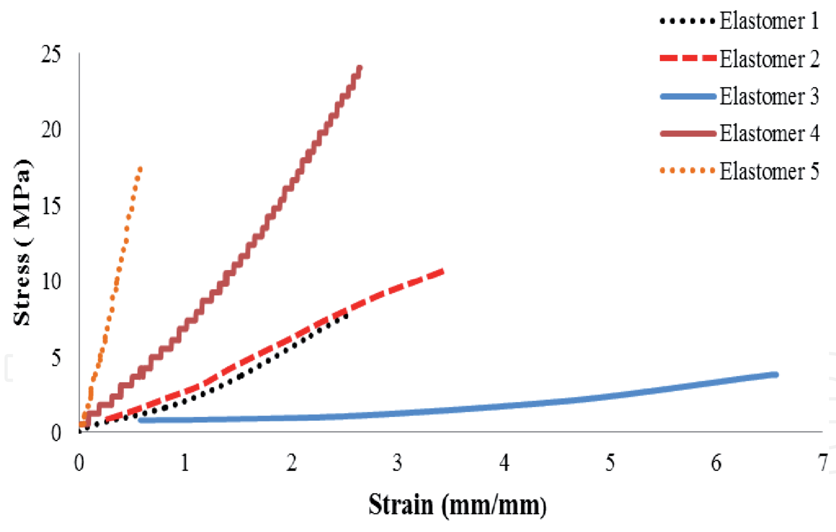

Figure 3.
Average stress-strain curves for the five elastomeric seal materials (right).

OR_m is the outer radius of the mandrel, IR_t is the inner radius of the SET before expansion, G is the initial radial gap between the elastomer seal and formation, and t is the seal thickness.

2. Numerical modeling

Compression of the SET elastomer seal against rock formation is modeled and simulated using the commercial finite element package ABAQUS; **Figure 4**. Based on the geometric layout of the problem, an axisymmetric model is used. The mandrel is moved through the tubular, expanding it and thus compressing the elastomer seal against the formation. Arruda-Boyce hyperelastic model is chosen to represent the material behavior of the elastomer. Elastomer is assumed to be perfectly bonded to the tubular. Coulomb friction model is used to represent the mandrel-tubular and seal-formation surface interactions. Formation is modeled as rigid, elastic, or elastic plastic. Seal length is varied from 50 mm to 400 mm, as seal lengths below 50 mm are not economically viable for either the manufacturers or the operators. Based on actual swell packer data, elastomer seal thickness of 5, 7, or 9 mm is modeled.

The expansion cone (mandrel) is made of hardened, heat-treated tool steel. It is therefore modeled as a rigid body. The tubular is modeled using 4-node bilinear axisymmetric quadrilateral elements with reduced integration. Dimensions of an actual 7⅝-inch solid expandable tubular are used; inner diameter of 174.625 mm and thickness of 9.525 mm. Material properties are obtained from tensile test data for actual unexpanded SET samples. Compared to normal steels, this expandable steel has an unusual elastic modulus of around 78 GPa. Poisson's ratio is taken to be 0.3.

Element type used for the elastomer seal is 4-node bilinear axisymmetric quadrilateral with hybrid formulation. Material coefficients for the Arruda-Boyce hyperelastic model for each elastomer are extracted from stress-strain data obtained from tensile tests conducted on the unswelled elastomers; **Figure 3**. As described above, the rock formation is modeled as rigid, elastic, and elastic-plastic. Formation properties are obtained from an actual oil field in the region. Variable mesh refinement is used in areas of large deformation for the tubular and elastomer seal; **Figure 4**.

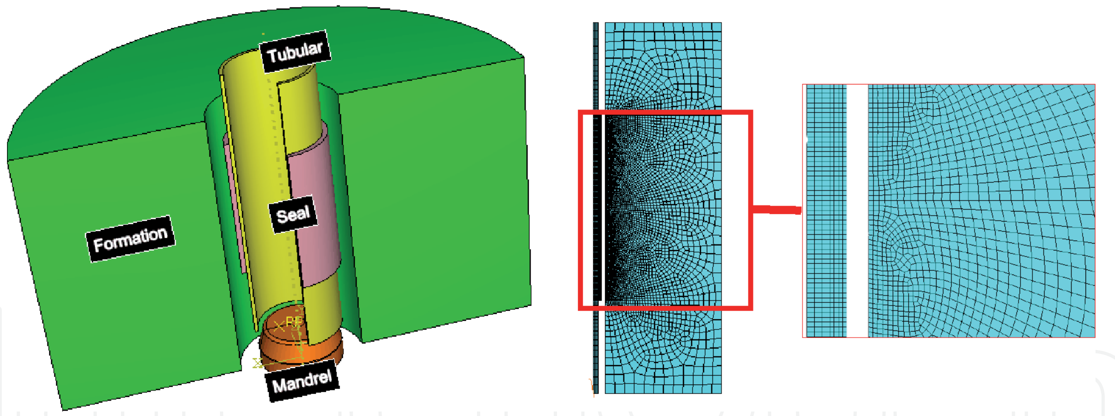

Figure 4.
Finite element model of SET expansion with swelling elastomer seal (left); meshing of the model, with enlarged view of central contact area between elastomer and formation (right).

3. Results and discussion

FE simulations have been run to study variations in seal contact pressure for different elastomer materials, expansion ratios, compression ratios, seal thickness, formation type, and tubular end conditions.

3.1 Elastomer material

Figure 5 shows the effect of using different swelling elastomers on sealing pressure along the seal length. Except near the ends of the sealing element, there is no significant pressure variation along the length of the seal. The ends have more freedom to deform, while the rest of the elastomer (along the entire seal length) is perfectly bonded to the steel tubular, so this observation is as expected. Elastomer E5 generates the highest contact pressure, while E3 yields the lowest. This result is in line with the fact that elastomer-5 has the highest modulus of elasticity, and the stiffer material produces larger forces. It is important to note that these results are based on elastomer properties in the un-swelled condition. When the elastomers swell, sealing pressure will be higher due to the combined effect of tubular expansion and elastomer swelling. Selection of the elastomer type for a particular SET application will depend on the actual field conditions such as temperature, water salinity, formation type, etc.

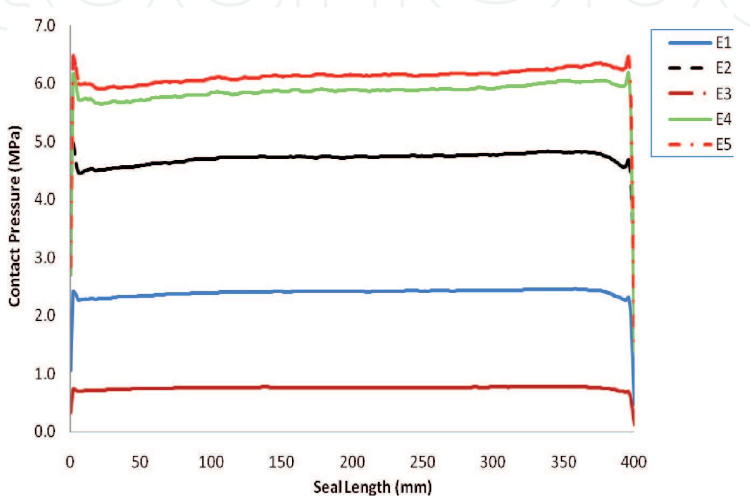

Figure 5.
Contact/sealing pressure along the seal length for different elastomer materials.

3.2 Expansion ratio

Effect of tubular expansion ratio on contact pressure along the length of the seal is shown in **Figure 6**. Obviously, larger amount of tubular expansion (higher value of *ER*) pushes the elastomer more against the formation, generating higher sealing pressure. Behavior along the seal length is interesting; contact pressure at the two ends is much higher, then drops down sharply and remains almost constant along the middle portion of the seal. The mandrel is conical in shape. Pressure starts to build up as the mandrel comes in contact with the tubular, and builds up sharply as the rest of the conical surface pushes against the tubular. After this initial build-up, the pressure drops down to almost a steady-state value. Mostly dependent on the variation in frictional forces (sticking to sliding), this initial rise and drop in pressure (known as *upsetting*) is typical of the process of extrusion, which is very similar to tubular expansion. Near the end of the seal, when the conical mandrel starts to lose contact with the tubular, a mirror behavior can be clearly observed.

3.3 Seal thickness

Effect of seal thickness on sealing contact pressure can be seen in **Figure 7**. Pressure curve for the thickest seal (9 mm) is the highest. Obviously, as the thickness increases, the compression ratio increases, generating higher contact pressure. In reality, this does not translate into the simplistic rule of *larger seal thickness for higher seal pressure*. Larger thickness of sealing elements will result in larger consumption of swelling elastomer, adding to both cost and weight. More thickness can also cause clearance issues for in-situ measurement devices. Moreover, too much sealing pressure can cause undesirable distortions. Optimum seal thickness will depend on the specific field conditions, elastomer material being used, and the amount of tubular expansion.

3.4 Formation type

Variation in sealing pressure along the seal length for different types of formation is shown in **Figure 8**. Highest contact pressure can be observed in the case when the formation is assumed to behave as a rigid material, and the lowest for elastic-plastic behavior. These observations are in line with intuitive reasoning. In the case of elastic and elastic-plastic formations, some amount of energy will be spent in elastic or plastic deformation of the formation. However, all energy will be

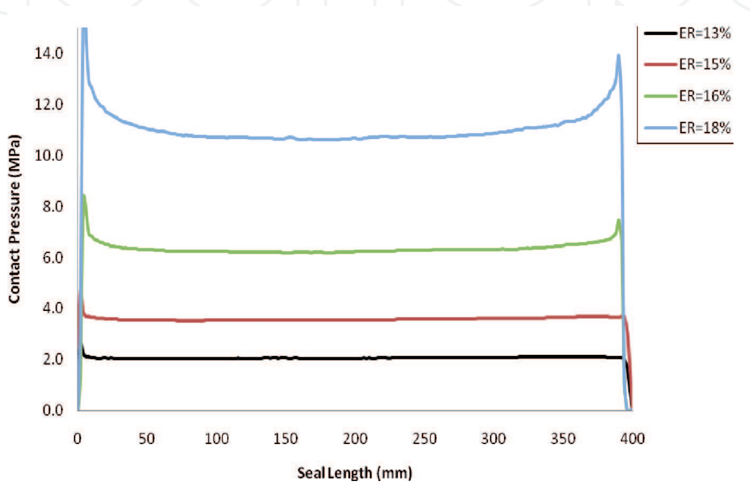

Figure 6.
Contact pressure along the seal length for different tubular expansion ratios.

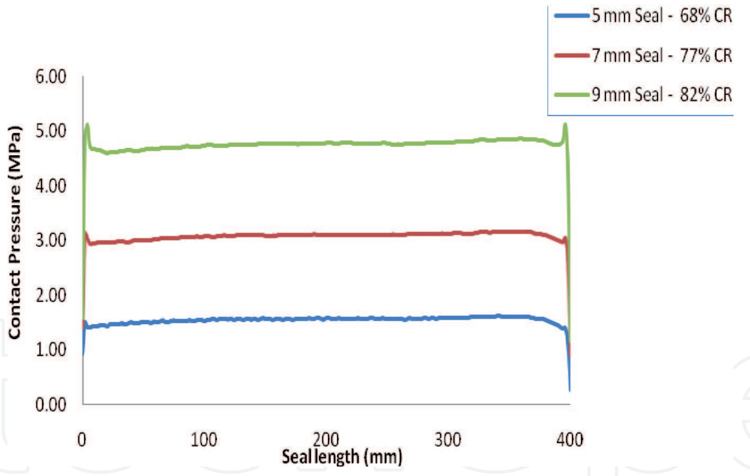

Figure 7.
Contact pressure along the seal length for different values of seal thickness.

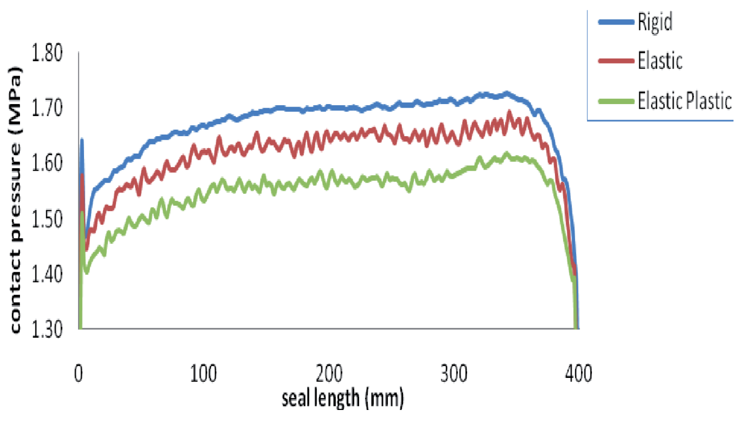

Figure 8.
Contact pressure along the seal length for different formation types.

used up for elastomer compression when we have a rigid formation, thus generating maximum contact pressure.

4. Conclusions

Behavior of swelling elastomer seals, when used in conjunction with solid expandable tubulars, has been simulated using the finite element package ABAQUS. Seal performance (in terms of contact pressure generated) was studied for variations in parameters such as elastomer material, tubular expansion ratio, seal thickness, tubular end conditions, and formation type. It was found that seal material can be a major factor contributing to sealing pressure. In addition, high contact pressures are observed for higher expansion ratios, larger seal thickness, and rigid formation type. This type of work on evaluation of seal performance, using material response of solid expandable tubulars and swelling elastomers actually being used in petroleum development operations, cannot be found in earlier published literature. Results from this study are useful both for proper selection and for design improvement of swell packers in SET applications.

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