Rupture analysis of rubber in the presence of a sharp V-shape notch under pure mode-I loading

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Abstract

The rupture behavior of styrene-butadiene rubbers (SBR) in the presence of a V-shape notch is investigated for the first time both experimentally and theoretically. In the experiments, V-notched samples of SBR are tested under tensile loading and their rupture displacements are determined. Afterwards and in the analytical field, the rupture loads of tested rubbers are predicted using the averaged strain energy density (ASED) criterion. The key idea of this criterion (i.e. the almost uniaxial state of stress field near the notch tip) is verified through non-linear finite element modeling. It is shown that good agreement exists between the predictions of the ASED criterion and the experimental results obtained for SBR. Moreover, the microscopic study of the ruptured surfaces of the notched SBR demonstrates its high roughness which can be attributed to the resistance of the rubber chains against the crack growth.

1. Introduction

Polymer-based materials are nowadays produced and utilized extensively in different industrial applications. They are used as packaging, solid molded forms for automobile components, composites for aircraft structures, adhesives for sticking two adherends, rubber for tires and gaskets, and a myriad of other applications [1]. Rubber, which has achieved a great deal of attention in engineering issues during the recent decades, is a subset of polymeric materials. The high extensibility and ability to undergo large elastic deformations during the stretch are among the particular properties of this type of polymer-based materials. It is worthy to note that these characteristics of rubber-like materials are related to their unique microstructure. While the atoms' bonding strength, in other words dominantly energy driven elasticity, is responsible for the behavior of traditional materials like metals, the rubber elasticity is mainly entropic [2]. Indeed, rubber is made up of long and entangled chains which are randomly oriented and form a network arrangement. Moreover, since the chains as a composition of thousands of sub-units are joined together with cross-links, they can easily return to their original shape when the external loading is removed [3] (see Fig. 1).

Fig 1

Fig. 1. A schematic figure of micromechanics of a rubber network.

On the other hand, the presence of geometrical discontinuities (e.g. cracks, corners and notches) in engineering structures significantly diminishes their load-bearing capacity [4]. However, unlike the crack nucleation which is often an undesirable object, a notch is usually introduced in the components deliberately due to the requirements of practical design [5]. As a stress raiser in components, the notch tip is a likely site for crack initiation and eventually failure of the structure. Therefore, because of the frequent existence of notches in engineering structures, investigation of a suitable criterion for fracture assessment of specimens weakened by notches is still an active research topic in the engineering.

Dealing with fracture prediction of notched brittle components, a wide variety of criteria has been proposed in the past. Some of these criteria are finite fracture mechanics criterion [6], [7], J-integral criterion [8], [9], theory of critical distance (TCD) [10], maximum tangential stress (MTS) criterion [11], generalized stress intensity factor-based criterion [12], equivalent material concept (EMC) criterion [13], [14], [15] and a criterion based on the combination of Novozhilov's and Irwin's criteria as investigated in Ref. [16]. However, the EMC criterion can be used for both brittle and ductile materials. On the other hand, strain energy density (SED)-based theories are among the criteria which have attained much attention because of their convenience in use. In general, the main concept of SED-based criteria is constructed on the idea that a continuum can be considered as an assembly of thousands of small building blocks each of them can store a finite amount of energy over its unit volume [17]. One of the suitable and convenient SED-based criteria is the averaged strain energy density (ASED) criterion [18]. So far, this criterion has been successfully utilized for fracture assessment of both polymeric [19], [20], [21] and non-polymeric [18], [22] materials weakened by notches. However, those studies dealing with notched polymeric materials have concentrated mainly on fracture prediction in polymeric components having linear elastic and small deformation behaviors like polymethyl-methacrylate (PMMA) and general purpose polystyrene (GPPS). To the best of the authors' knowledge, no experimental or analytical work has been performed in the past on the fracture assessment of notched components made of polymeric materials with large deformation behavior like rubbers.

Considering the mentioned points, the present study is concentrated on the rupture assessment of notched rubber parts having large deformation behavior. The main purpose of the current study is twofold:

- First, to provide a set of test data on rupture of rubbers weakened by sharp V-notches. These experimental data, which have been performed for the first time in the current study, can be useful for future studies as well.

- The second aim is to extend the application of the ASED criterion to notched rubbers subjected to pure mode-I loading. Indeed, a novel method has been recently developed by the present authors for generalization of the conventional ASED criterion to cracked rubber specimens [23], [24]. Hence, in this study, an attempt is made to generalize the use of the ASED criterion to hyperelastic materials weakened by sharp V-notches. The presented method is mainly based on the nearly-uniaxial state of stress fields near the notch tip in rubber-like materials. This key point is also elaborated via the finite element modeling (FEM).

2. Experimental procedures

2.1. Materials and sample preparation

Styrene–butadiene rubber (SBR), which is extensively used nowadays as one of the main components of the elastomeric matrices, has attained great attention in various industrial applications like automotive tires, cable applications, and sporting goods [25], [26]. Therefore, investigation of its fracture mechanics has a great importance.

Styrene-butadiene rubber (SBR) with a Mooney viscosity of ML (1 + 4, 125°C) = 55 and styrene content of 23.5% (SBR1502), which has been supplied by Bandare-Imam Co in Iran, was used. For preparation of a compound, at first, SBR was mixed with calcium carbonate (CaCo3), stearic acid (St-A) and zinc oxide (ZnO) on the two roll mill for about 10 min. Then, a conventional sulfur curing system consisting of sulfur (S) and accelerators was added into the compound at the room temperature. The compound was finally vulcanized in a hydraulic hot press (400S Polystat model, Germany) at a temperature of 155°C and for an optimum curing time (t90) of 6:18 (min:sec). It is useful to note that the curing time of t90 was obtained from an oscillating disk rheometer (ODR, Monsanto 100S UK) and according to the ASTM D5289 test method. The graph of torque-time achieved from the rheometer is shown in Fig. 2. Moreover, the formulation of the prepared sample is given in Table 1.

After preparation of the rubber sheets with the thickness of 1.5 mm, the test-pieces including the dumbbell-shaped and V-notched samples were cut from the sheets. More detail about the dimensions and geometry of the samples is explained in the following sub-section.

2.2. Mechanical tests

In order to achieve the mechanical characteristics of the SBR, tensile test was performed on the dumbbell-shaped sample, using a Santam universal testing machine (Iran) at the crosshead speed of 1 mm/min. The geometry and dimensions of the tensile test sample is illustrated in Fig. 3. It should be further noted that in order to have an accurate measurement of the strain, a Canon CMOS camera was also used during the tensile test. In this regard, two white points, shown in Fig. 3, were painted on the sample.

Fig 3

Fig. 3. Geometry and dimensions of dumbbell-shaped sample (White points on the surface were used for accurate determination of strain via the used camera).

Moreover, in order to perform the fracture tests, at first, single edge notch (SEN) samples were prepared via introducing a sharp V-notch to the rubbers using sharp razor blade. Four different notch depths (i.e. a = 4, 8, 10, 12 mm) were investigated in this study. Related geometry and dimensions of the SEN samples are shown in Fig. 4.

Fig 4

Fig. 4. Geometry and dimensions of the SEN samples.

Afterwards, the tensile fracture tests in mode-I loading conditions were conducted on the notched components with a loading rate of 1 mm/min. Moreover, for precise determination of the rupture initiation in the notched samples, some white speckle points were painted near the notch tip (see Fig. 5). Then, using the camera, the onset of rupture was determined by tracing the obtained images. The initiation of rupture was defined by the occurrence of a significant increase in the cut-length. Doing so, the rupture displacements of tested notched samples were achieved.

Fig 5

Fig. 5. A typical SEN sample placed in the fixture and subjected to the mode-I loading.

3. Theoretical background

Fracture criteria can be generally classified into two main categories: stress (or strain)-based criteria and energy-based ones. In the case of energy-based criteria for rubber-like materials, the tearing energy model, developed by Rivlin and Thomas [27], was among the first criteria. This criterion is indeed an extension of Griffith's energy release rate model to elastomers. According to the tearing energy approach, the crack extends if the elastic strain energy stored in the test piece is sufficient to overcome the surface energy of the material required to form a new surface [28]. On the other hand, the ASED criterion, which is again an energy-based model, has a nearly similar basis to the tearing energy. However, instead of investigating the surface energy of material, the ASED criterion deals with the strain energy stored in a control volume surrounding the point of stress concentration. It is worth mentioning here that the strain energy is defined as the energy stored in a member due to the strain (i.e. deformation). Moreover, the SED value (denoted by) for a material is generally defined as the strain energy per unit volume [24].

In the following, a review of the ASED criterion for cracked rubbers, which has been recently developed by the authors, is presented. Next, the extension of the criterion to the notched rubber samples is developed and discussed.

3.1. ASED criterion for cracked rubbers

According to the ASED criterion, fracture in a cracked sample occurs when the average of SED in a defined control volume (with the critical radius of Rc) reaches a critical value Wc. It can be realized that determination of Rc and Wc is of paramount importance when using the ASED criterion.

For brittle and quasi-brittle materials, which show linear elastic and small strain behavior, the following relations have been suggested for Wc and Rc[29], [30]:

(1)

where E and ν are the elastic modulus and Poisson's ratio of the material, respectively. Furthermore, KIc and σt respectively denote the fracture toughness and the ultimate stress of tested material in the conventional uniaxial tensile test.

However, because of the large deformation nature of rubber parts, the values presented in Eq. (1) cannot be directly used for these types of materials. To overcome this challenge and to facilitate the use of the ASED criterion in rubbers, the present authors have recently developed a new procedure for determination of the critical values of Wc and Rc in cracked components made of rubber-like materials [23], [24]. According to this method, the value of Wc in a cracked rubber sample can be obtained from the uniaxial tensile test date as follows:

(2)

Although the conceptual detail of the above relation can be found in the original Refs. [23], [24], it is worthy to remind here that the fundamental point of Eq. (2) is the nearly-uniaxial state of stress field near the crack tip in rubber-like materials.

3.2. Extension of ASED criterion to notched rubbers

As stated earlier, for the use of ASED criterion in a material, it is important to find the value of WC as well as the shape of control volume and its radius. In the following, an attempt is made to extend the use of the above-mentioned procedure to notched samples made of rubber-like materials.

3.2.1. Determination of the critical value of Wc

For determination of the value of Wc in rubbers weakened by notches, an equation similar to Eq. (2) can be used provided that the almost uniaxial state of stress field next to the notch tip exists in a V-notched sample. As elaborated later based on the FEM results (see Section 5.3), the nearly-uniaxial nature of stress fields near the V-notch tip is also established in hyperelastic materials. In other words, it can be expected that similar models in the microscale exist in the rupture of a notched rubber and its uniaxial tensile test [31]. Therefore, it is suggested that the critical value of Wc for a notched rubber subjected to pure mode-I loading is equal to the critical value of SED achieved from its uniaxial tensile test, i.e.:

(3)

At this point, it is appropriate to discuss briefly about determination of the value of Wc based on the tensile test data and selected hyperelastic SED function. The SED function, W, is used for characterization of mechanical properties of rubber-like materials. This function can be expressed in terms of the principal invariants of the right Cauchy–Green deformation tensor (i.e. I1,I2,I3) [32]. Furthermore, because of the incompressible nature of rubber-like materials, it can be proved that the SED function is independent of the third invariant I3. Thus, the following relation can be written:

(4)

Moreover, I1 and I2 in the condition of incompressibility are defined as follows:

(5)

On the other hand, one of the most used hyperelastic material models for rubbers, which is also used in the current study for characterization of the target SBR, is the Mooney-Rivlin (M-R) model [33], [34]. According to this model, the SED function for an incompressible material is explained as follows:

(6)

where C1 and C2 are material constants. Moreover, Ji = Ii − 3, (i = 1, 2).

For determination of the critical value Wc based on the M-R model and in a uniaxial tensile test, the critical value of J1 and J2 (namely J1c and J2c) should be computed. In this regard, if the final stretch of tested rubber in the uniaxial tensile test is equal to λten, J1c and J2c can be expressed as follows [24]:

(7)

Thus, the critical value of SED function based on the M-R hyperelastic material model can be obtained as follows:

(8)

3.2.2. Determination of the shape and radius of control volume

The calculation of Rc for hyperelastic materials containing sharp V-notches should be performed in two stages: first, determination of the shape of control volume surrounding the notch tip and then, obtaining the critical value of Rc.

For the first task, the practical point suggested by Ref. [30] should be taken into consideration. According to this point, the shape of control volume around the stress concentration zone in the ASED criterion can be determined based on the contour lines (i.e. isosurfaces) of the SED. Using this helpful tip, the plot of SED contour lines in a region near the notch tip for a sample notched rubber (with the notch depth of 4 mm) is drawn in Fig. 6. It is important to note that the contours presented in Fig. 6 are plotted in the initial (i.e. undeformed) configuration.

Fig 6

Fig. 6. The contour lines of SED near the notch tip for a SEN hyperelastic material in the undeformed configuration.

As can be seen in Fig. 6, the contour lines of SED near the notch tip in the undeformed configuration are in the shape of circles around the notch tip. Moreover, it is found that this circular shape is independent of the notch depth and the load applied in finite element (FE) simulations. As a result, it is concluded that same as that similar to the case of brittle materials, the control volume for a sharp V-notched sample made of rubber is a sector of circle embracing the notch tip. It may be useful to note that, as can be seen in Fig. 6, the control volume is slightly eccentric relative to the notch tip. However, the general form of control volume is still a circle. Similar to this condition was reported in Refs. [35], [36], where the circle of plastic zone near the V-notch tip for a mode III elastic-plastic problem had a small movement away from the notch tip. As a result, although the SED contour lines are not exactly concentric with the notch tip, the shape of control volume in the ASED criterion for the tested rubber is still a circle. Therefore, it is supposed that this small movement of the control volume has the least effect on the ASED criterion, and in fact, the shape of control volume is more important than its center. The good agreement between the theoretical estimations of the ASED criterion and the related experimental results in Fig. 16 can confirm this assumption.

In the second stage, as stated in Ref. [37], the presentation of a closed-form relation for Rc in hyperelastic materials is far from easy. However, a suitable procedure for obtaining the value of Rc is presented in Refs. [23], [24] as follows:

For an arbitrary sample and in a critical condition (i.e. when the experimental rupture load is applied in the finite element model), the curve of SED values () against different radii of the control volume should be plotted. Then, the radius at whichis determined as the critical value of control volume radius, Rc.

It should be further noted that the good agreement between the predictions of ASED criterion for cracked rubber components and the related experiments investigated in Refs. [23], [24] confirms the reliability of the above-mentioned procedure for determination of the value of Rc in hyperelastic materials.

4. Finite element modeling

Numerical approaches like FEM have become an important part of engineering design and analysis because of their benefits and convenience in use for engineers. Moreover, the rapid advances in the field of computer aided engineering (CAE) have facilitated the use of FEM in engineering problems.

In the present study, FEM was used in order to quantify the value of SED,, in the selected control volume. Moreover, the circular shape of control volume (see Fig. 6) near the notch tip in the target rubber has been obtained via FEM. On the other hand, because of some difficulties encountered in the modeling of large deformation behavior, the tip of V-notch was modeled with a very small radius (i.e. notch tip radius of 0.001 mm). In fact, since in the preparation of sharp V-notches, the notch tip is not perfectly sharp, the consideration of this radius for the notch tip is reasonable. Fig. 7 illustrates a typical mesh pattern used near the notch tip in a sample model. As can be seen from Fig. 7, very fine mesh was employed near the notch tip as a zone of stress concentration. It is also useful to mention that 2D plane stress elements with quadratic order and reduced integration were used in this study.

Fig 7

Fig. 7. A typical mesh pattern used near the notch tip in a sample SEN model.

5. Results and discussions

In this section, first, the experimental data for the uniaxial tensile loading and fracture tests are presented. Then, based on the FEM results, the dominant uniaxial nature of stress field in the proximity of notch tip is proved numerically. Finally, the extended ASED criterion for rubbers weakened by sharp V-notch is verified according to the related experiments.

5.1. Determination of a hyperelastic material model

The first step for FEM as well as employing the ASED criterion, is to select a reliable hyperelastic material model which can represent properly the behavior of rubber. Therefore, according to the tensile test data obtained for the tested SBR in terms of stress – elongation, a curve fitting analysis was performed and finally, the M-R material model was found to have the best agreement with the experiment (see Fig. 8). The material constants of the M-R model were equal to C1 = 227.9 KPa and C2 = 552.3 KPa.

Fig 8

Fig. 8. Stress-elongation curve achieved for SBR under uniaxial tensile loading.

It may be useful to compare the predictions of other material models with those obtained for the M-R model. In this regard, the stress-elongation predictions of the Arruda-Boyce model as well as the Gent one, based on the constants reported in Table 2, are assessed and the results are shown in Fig. 8.

Table 2. Material constants obtained for three different hyperelastic models.

As can be seen in Fig. 8, the two other models (i.e. Arruda-Boyce and Gent models) could not follow the experimental path for the tested SBR accurately. The relatively low values of R-square (which indicates the appropriateness of fit) obtained for the Arruda-Boyce and Gent models confirm the poor predictions of these models in comparison with the Mooney-Rivlin one.

Moreover, as it can be inferred from Fig. 8, the rupture stretch of the SBR in the tensile loading is equal to λten = 2.67. This value will also be used later for computation of the critical value of SED, Wc.

5.2. Qualitative observation on tearing process

The fracture tests for SEN specimens were performed until the final rupture of the samples. Moreover, as stated earlier, the onset of rupture was determined by using the camera during each test. The camera time step for capturing every two consecutive images was set to be equal to 10 seconds. Doing so, the critical displacements at the rupture initiation for different SEN specimens are summarized in Table 3.

Table 3. The rupture displacements of different SEN samples.

Moreover, the stress-strain curves of different tested SEN samples, recorded up to the final tearing points, are extracted and the results are depicted in Fig. 9. It is important to note that unlike the case for usual brittle materials (e.g. PMMA), the rupture in SEN rubbers initiates before final tearing of the samples. The points of rupture initiation are specified in Fig. 9 by small stars.

Fig 9

Fig. 9. Nominal stress-strain curves of different SEN specimens (Stars denote the rupture initiation points).

It can be seen from Table 3 and Fig. 9 that as the notch depth increases, the critical displacement (or strain) of the sample decreases. It is due to the fact that with increasing the notch depth, the remaining ligament of the specimen reduces and hence the resistance of the sample decreases.

Fig. 10 shows the progressive deformation of the SEN sample with notch depth of a = 8 mm during the fracture test. The large deformation behavior of SBR and sever notch tip blunting can be seen in Fig. 10. Indeed, the notch initially opens and remains nearly symmetric with respect to the notch bisector line. Then, the rupture initiates from a position where a small defect (e.g. a crack) is present in the notch border. Finally, the deviated crack propagates relatively slow to the end of the specimen ligament and complete rupture of the rubber occurs.

Fig 10

Fig. 10. Progressive deformation of the SEN specimen with notch depth of 8 mm during the fracture test.

Another notable point in Fig. 10 is a nearly stable form of fracture for the notched rubber sample. To be more precise, unlike the unstable and sudden fracture of brittle polymeric materials having small strain behavior (e.g. PMMA and GPPS), in the tested SBR and after the crack initiation in the notch border, it takes some considerable time to final rupture of the sample. This behavior can be attributed to the physics of rubber where the entangled chains can resist against the crack growth and thus, hinder the final rupture of the sample. Moreover, this phenomenon can also be justified because of the sever blunting of the notch tip in rubber-like materials when compared to brittle polymers. In other words, this sever blunting can reduce the stress concentration near the notch tip in rubber-like materials and therefore, postpones the time required for final rupture of the sample.

For further investigation of the tearing process, some microscopic images for different positions of the ruptured SEN specimen (with the notch depth of 8 mm) are illustrated in Fig. 11. In this figure, the microscopic images numbered with 1 and 2 are related to the notch border where a razor blade was used to introduce the initial notch. The other three images show the ruptured surfaces of the SEN sample after the tearing process. It is clearly seen from the images that the regions cut by the razor blade have a very smooth surface, while the ruptured surfaces possess a high roughness. This observation can be considered as a suitable evident for the point mentioned previously that the rubber chains resist against the crack growth and thus, the roughness of the ruptured surfaces is expected to be higher in comparison to the surfaces cut by a razor blade.

Fig 11

Fig. 11. The microscopic pictures of different positions in the ruptured sample.

5.3. Stress fields near the notch tip

As stated earlier, the important point regarding the extension of the ASED criterion to notched rubber-like materials, based on the procedures suggested in Section 3.2, is the nearly-uniaxial nature of stress fields near the tip of sharp V-notch. This key point is proved numerically in this subsection.

For investigation of the stress field near the notch tip, FEM was performed for the SEN sample with the notch depth of a = 4 mm as a typical sample. Moreover, a circumferential path located at r = 0.2 mm, as a path in the vicinity of the notch tip, was selected. Then, the values of Max. and Min. in-plane principal true stresses were extracted in the mentioned path for this sample. Fig. 12 shows a plot of Max. and Min. in-plane principal true stresses in the circumferential path.

Fig 12

Fig. 12. The variation of the Max. and Min. in-plane principal true stresses through the circular path of radius r = 0.2 mm.

For the ease of comparison, the ratio of Max. to Min. in-plane principal true stresses was calculated and the result is illustrated in Fig. 13. It is important to note that this ratio can be regarded as an appropriate indicator of the degree of uniaxiality.

Fig 13

Fig. 13. Max. to Min. ratio of in-plane principal true stresses through the circular path located at r = 0.2 mm.

As can be seen in Fig. 13, the stress ratio is larger than 23 through the selected path. Therefore, it can be inferred that a nearly-uniaxial state of stress field close to the V-notch tip occurs in rubber-like materials. This numerical data is in agreement with the result of Ref. [40] where Wang and Gao analytically proved that the dominant stress next to the notch tip is in the state of uniaxial.

At this point, it may be interesting to compare the stress ratio obtained for the tested rubber with that of a pure linear elastic material. In this regard, the stress ratio was determined for GPPS (as a brittle material with linear elastic behavior) using the elastic modulus and Poisson's ratio equal to 3100 MPa and 0.34, respectively [11]. Moreover, the same geometry as considered above for the V-notched rubber was utilized in the FE simulation of GPPS and then, the ratio of Max. to Min. in-plane principal stresses was drawn in Fig. 14. It is important to note that because of the linear elastic nature of GPPS, the stress ratio for this material is independent of the load applied in the FE model.

Fig 14

Fig. 14. The ratio of Max. to Min. in-plane principal stresses for GPPS as a brittle and pure linear elastic material (the circular path located at r = 0.2 mm).

As can be seen in Fig. 14, the minimum value of stress ratio for GPPS is about 1.2 and occurs along the notch bisector line, while the minimum stress ratio in the tested rubber was about 23. As a result, the minimum value of stress ratio in target SBR is about 20 times larger than that of GPPS.

5.4. Dependency of ASED value to the element size

One of the main advantages of the ASED criterion, which has been proven previously under the linear elastic and elastic-plastic conditions, is its independency to the size of elements used for FE modeling [41], [42]. This feature is examined here for hyperelastic materials too.

In order to investigate the effect of coarse and fine meshes on the value of SED averaged over the control volume in hyperelastic materials, eight different mesh patterns were utilized in the FE models by considering a radius of control volume equal to Rc = 0.64 mm (that is the critical size of control volume obtained in the next section for the tested SBR). Table 4 summarizes and compares the results.

Table 4. Effect of element size on the ASED value.

Number of elements considered in the control volume	ASED value (MJ/m3)	Variation (%)

As it is seen from Table 4, the variation of the ASED value by reducing the number of elements from about 4000 to 40 is less than 0.1%. Therefore, the mesh independency of the ASED value is maintained in hyperelastic materials as well. This salient property makes it possible to significantly reduce the computational cost of the finite element analyses, especially in rubbers which have both geometrical and material types of non-linearity. As a result, one can obtain the ASED value in hyperelastic materials with a good accuracy by using a coarse mesh.

5.5. Synthesis of experimental fracture data based on ASED criterion

In order to verify the usefulness of the extended ASED criterion for the notched rubbers, the experimental results of present study are utilized in this subsection. In this regard, the first step is the computation of the critical values of Wc and Rc.

According to the constants of the M-R hyperelastic model for the target SBR (i.e. C1 = 227.9 KPa and C2 = 552.3 KPa) as well as the final rupture of SBR in the tensile loading (i.e. λten = 2.67) obtained in Section 5.1, the value of Wc can be determined. By substantiation of these values into Eq. (8), the critical value of SED for the tested SBR is obtained as Wc = 2.48 MJ/m3.

On the other hand, the graph of SED values versus different radii of control volume for the SEN sample with the smallest notch depth (i.e. a = 4 mm) and by applying its experimental displacement (i.e. uy = 15.2 mm) is plotted in Fig. 15. Then, based on the procedure explained earlier in Section 3.2.2, the radius at which the value of SED reaches Wc = 2.48 MJ/m3 can be regarded as the critical radius of control volume. Doing so, this value is found to be Rc = 0.64 mm for the tested rubber.

Fig 15

Fig. 15. Determination of the critical value of control radius (Rc) for SBR.

After determination of its basic parameters, the ASED criterion can now be employed for rupture assessment of the fracture tests. To this end, FEM was carried out for each SEN sample. In addition, because of the non-linear nature of the problem, the principle of superposition could not be utilized. Thus, the magnitude of applied displacement in FEM was increased until the value of SED in the defined control volume with the radius of Rc = 0.64 mm reached the critical value of Wc = 2.48 MJ/m3. Therefore, the corresponding applied displacement in FEM can be regarded as the theoretically determined rupture load of each sample based on the ASED criterion. Fig. 16 demonstrates the prediction of the ASED criterion in comparison with the experimental data presented in Table 3. It is clear in Fig. 16 that the ASED criterion can predict well the rupture of notched rubber components. This good agreement reveals the high efficiency of the ASED criterion in materials with large deformation behavior like rubbers. However, it would be surely useful to do further experiments in order to verify the ASED criterion in rubber-like materials considering more sets of data.

Fig 16

Fig. 16. Comparison between the experimental and theoretical rupture displacements.

6. Conclusions

The essential points of the present paper were twofold:

- Some experimental fracture tests were performed for the first time on sharp V-notched samples made of rubbers. The prepared specimens were made of styrene-butadiene rubber (SBR).

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Secondly, the averaged strain energy density (ASED) criterion was extended to use in notched materials with large deformation behaviors like rubbers and soft materials. Indeed, the ASED criterion, as a suitable and widely used criterion in mechanical engineering, was applied extensively in the past for rupture assessment of materials with small strain behavior. However, because of restriction of the main parameters of the criterion (i.e. critical values of strain energy density, Wc, and radius of control volume, Rc) to small deformation condition and linear elastic materials, these previously determined values cannot be directly used for materials with non-linear and large strain behavior. Hence, this extension was of great importance.

The extension was based on the idea that the state of stress field near the notch tip in rubber-like materials is nearly in the state of uniaxial. After verifying this key point via the non-linear finite element analysis, the critical value Wc was analytically obtained for the Mooney-Rivlin (M-R) hyperelastic material model. The M-R model had the best matching with the tensile test data for the tested SBR. Then, the ASED criterion was utilized for rupture assessment of the corresponding experiments. Good agreement was found between the experiments and the predictions of the ASED criterion. Additionally, it was proved that the shape of control volume around the notch tip, used in the ASED criterion, is a circular sector in hyperelastic materials.