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# Mechanical characterization of Araldite LY 564 epoxy: creep, relaxation, quasi-static compression and high strain rate behaviors

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## Abstract

A comprehensive mechanical characterization of a commercially available hot curing epoxy system (Araldite® LY 564 with Aradur® 2954, HUNTSMAN Corp.) is performed including compression tests at quasi-static and high strain rates, as well as creep and relaxation tests. High strain rate tests (770/s and 875/s) are conducted by using a split-Hopkinson pressure bar (SHPB) apparatus and compared with the quasi-static compression tests at three strain rates (0.001/s; 0.01/s; 0.1/s). Elasticity modulus and yield stress increase with increasing strain rate, for both quasi-static and high strain rate conditions. The change in the mechanical behavior from quasi-static to high strain rate conditions is quite prominent. While strain rate changes from 0,001/s to 875/s, elasticity modulus increases from 1465 to 3193 MPa (118% increase) and yield stress from 119 to 204 MPa (72% increase). The evident exponential hardening at the viscoplastic region seen on quasi-static stress–strain curves is not observed at high strain rates. Creep tests are performed for three different stress levels (50, 100 and 200 MPa) and 120 min (7200 s). In addition, relaxation tests are done for three different strain levels (3.16, 7.15 and 35.5%) also for 120 min (7200 s). Creep compliance and relaxation modulus are calculated and plotted. It is observed that creep strain values at the stress levels lower than the yield point are lesser compared to creep strain values around yield strength since rate dependency is increasing with increasing stress. Creep at the hardening region is not prominent due to polymer chain entanglement. Stress drop during relaxation is increasing with the increasing strain level.

**Keywords** Epoxy · SHPB · Compression · Creep · Relaxation

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## Introduction

Since their first commercial production in the late 1940s epoxy resins reached a wide range of applications in various industrial fields; thanks to their excellent adhesion, chemical and heat resistance, good-to-excellent mechanical properties and very good electrical insulating properties [1]. But it is also well known that the utilization of such materials as structural members requires a comprehensive mechanical characterization due to their time-dependent mechanical behavior. This well-needed characterization includes creep and relaxation tests, and also high strain rate tests since the components are exposed to impact and/or ballistic loads.

In the relevant literature, quasi-static and high strain rate behaviors of various epoxy resins and their composites are investigated. In the work by Shadlou et al. [2], the effect of strain rate on the mechanical behavior of pure epoxy resin (Araldite LY 564) and graphene–epoxy nanocomposite is investigated by quasi-static compressive and tensile tests. Compression tests are performed at strain rates of 0.01, 0.1, 1, 10/s. It is reported that yield strength and modulus of elasticity both increase with increasing strain rate. No high strain rate, creep or relaxation tests are performed. The high strain rate (1000/s–12,000/s) behavior of epoxy resin (DER 353) is investigated by Tamrakar et al. [3] in addition to quasi-static (0.001/s) compression loading. Elastic modulus increased from 2.75 to 4.1 GPa and yield stress increased by a factor of 2.6 when strain rate increased from 0.001 to 12,000/s. Jordan et al. [4] investigated the compressive behavior of Epon 826 epoxy across a range of strain rates, from 0.01/s to 10,000/s. Almost linear dependence on strain rate is observed for yield stress. Another experimental investigation is performed by Colak et al. [5]. Mechanical properties of epoxy resin (Fibre Glast, System 2000 with 2120 hardener) are determined under dynamic loading (SHPB test). Experiments are performed at two different strain rates (1500 and 2350/s). With increasing strain rate, both yield strength and elasticity modulus increased. Similar results are reported by Goglio et al. for an epoxy adhesive (Henkel Loctite Hysol 9466). The experimental tests have been performed at the range of 0,001/s to 3000/s using a hydraulic universal testing machine and a tension–compression Hopkinson bar apparatus. The results show that the yield strength rises significantly with increasing the strain rate [6]. In brief, it can be stated that for epoxy materials, both elasticity modulus and yield stress increase with increasing strain rate [7–11].

There are a number of works in the literature to characterize the creep and relaxation behavior of epoxy resins and their composites. In the work by Theocaris[12], viscoelastic properties of epoxy resins (H-100-40, C-100-0-8) were obtained by uniaxial creep and relaxation tests in 1962. Epoxy resins have extensive applications in a wide range of different fields. Creep compliance and relaxation modulus values are used as material parameters in commercial FEM solvers like ABAQUS. In 1996, Lee et al. [13] used DOW DER 332 epoxy resin to conduct creep and relaxation tests to determine creep compliance and relaxation modulus of the material for different test times (28, 126, 503, 2013 min for creep,

1, 2, 4, 8 h for relaxation). A more recent experimental work is performed by Ornaghi et al. [14] for the creep and recovery behavior of carbon fiber epoxy composites under low-stress loading. Four different laminates with varying fiber orientations are tested. It is stated that the creep behavior is highly related to the ply angle up to 60°; with increasing ply angle, creep strain also increases due to the increasing chain mobility. A related work, on the interfacial effects of the creep behavior of carbon fiber epoxy composites, is done by Almeida Jr. et al. [15]. It is reported that the creep strain increases from longitudinal to transversal fiber orientation and by increasing the temperature. Another experimental work by Almeida Jr. et al. [16] is reported for the creep and relaxation behavior of carbon fiber epoxy composites, for three different fiber orientations. The value of stress relaxation modulus overtime for the studied laminates is found to be decreasing with increasing fiber angle. The long-term creep behavior of epoxy composites, reinforced with a different fiber material, E-glass, is investigated by Nosrati et al. [17]. Creep tests are performed for the short term, and then, time–temperature superposition principle is applied to obtain long-term behavior. Results showed that the creep compliance increases with increasing constant stress. The work well proves that the time–temperature superposition principle can be used to decrease the cost of long-term creep tests. A detailed literature review reveals that no recent research has been made for determining the viscoelastic properties of pure epoxy resins. It is also comprehended that the determination of viscoelastic properties of pure epoxy resin is important and obligatory to better understanding of the time-dependent mechanical behavior of its composites. Therefore, it can be said that a comprehensive experimental characterization of mechanical properties for up to date epoxy materials, which this work aims, is a considerable contribution to the existing literature.

A detailed mechanical characterization of epoxy (Araldite LY 564) is performed in this work. The characterization includes compression behavior at quasi-static (0.001–0.1/s) and high strain rates (770–875/s) and also creep and relaxation behaviors. To experimentally obtain such data, a compressive split- Hopkinson pressure bar (SHPB) is used to investigate the dynamic mechanical behavior of Araldite LY564 epoxy at high strain rates. In the design of components made from polymers and polymer matrix composites, time-dependent behaviors are also important. Therefore, creep behaviors at different stress levels and relaxation behaviors at various strain levels are investigated. The creep and relaxation time is selected as 120 min (7200 s). It is observed that the mechanical properties such as elasticity modulus, yield stress and ultimate stress increase dramatically under dynamic loads.

## Materials

Araldite LY564 (Bisphenol-A) and Aradure 2954 (cycloaliphatic polyamine hardener) are used as epoxy resin and hardener materials, respectively. The epoxy system supplied from the Huntsman Corporation has a high glass transition temperature and elasticity modulus due to its high cross-linked structure. Compared to other epoxy resins, the cured epoxy system shows excellent mechanical, dynamic and thermal

(hot/wet) properties and good chemical resistance and reactivity [18]. Therefore, its application areas are changing from automotive technologies to ballistic-armor applications.

### Specimen preparation

To prepare the specimens, the hardener is added to the epoxy with a weight ratio of 100:35, as suggested by the supplier. The mixture is then mixed using a magnetic stirrer for 20 min at 750 rpm. Afterward, the mixture is degassed in a vacuum chamber at room temperature for 90 min. After degassing, the mixture is poured into the RTV silicone molds and cured at 80 °C for 1 h followed by a post-curing, at 160 °C for 4 h.

## Experimental work

Tests performed on the specimens prepared with the procedure given above are as follows:

1. Compression tests (at three different strain rates (1.E-3, 1.E-2 and 1.E-1/s) at room temperature)
2. Split Hopkinson pressure bar tests (at 2 and 3 bars)
3. Creep tests (120 min (7200 s) creep tests at three different stress levels)
4. Relaxation test (120 min (7200 s) relaxation tests at three different strain levels)

### Quasi-static compression tests

The quasi-static compression tests are performed using Instron 5982 (100 kN capacity) universal static test device. Tests are conducted on the cylindrical-shaped specimens with a diameter of 11 mm and a length of 10 mm at room temperature for different strain rates. To determine the viscoelastic and viscoplastic behavior of the material, compression tests are performed at three different strain rates (0.001, 0.01, 0.1/s). At least three tests are performed for all strain rates and the means are reported. The stress–strain curves obtained from the repeating tests are observed to be almost overlapping. Therefore, it can be stated that the reproducibility of the tests is fairly good. The compressive stress–strain curves for three different strain rates are presented in Fig. 1.

As can be seen from Fig. 1, the elasticity modulus and yield stress increase with increasing strain rate. Negligible rate dependency is determined at the viscoelastic region. No necking is observed in the yield region, followed by an inconspicuous strain softening, and a pronounced nonlinear strain hardening. These results are found to be compatible with the results in the existing literature [19].

Further investigation of the compression tests reveals that the time dependency for the elastic modulus is quite limited. As it is known, the elastic deformation mechanism is occurred by the elastic elongation of the polymer chains.

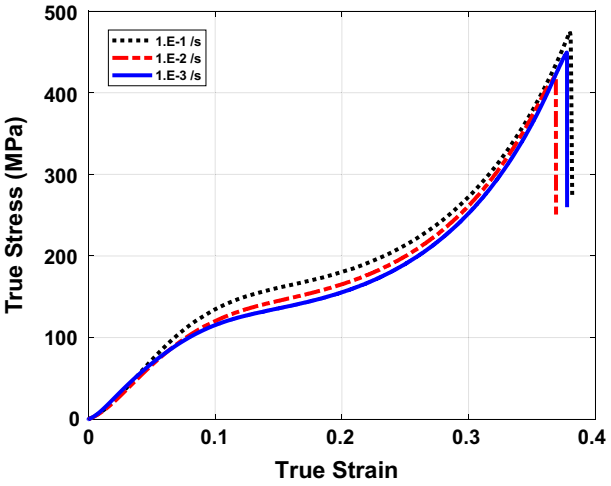



**Fig. 1** True stress–strain response of pure epoxy (Araldite LY564) at three different strain rates (1.E-3, 1.E-2, 1.E-1/s)

This phenomenon can be explained by the covalent bonds between the polymer chains reach the length of the chain and distort [20]. The intense crosslinking in Araldite LY 564 epoxy strengthens the covalent bonds between the polymer chains and reduces the effect of strain rate on the elastic region.

While strain softening and strain hardening after yield are observed in most epoxy materials, strain-softening behavior was not observed in Araldite LY564 epoxy. It exhibits nonlinear strain hardening without softening after yield. The peak point of the region where linearity ends and nonlinearity begins in the stress–strain curve is defined as yield stress. That is, the point where the slope of the stress–strain curve is zero for the first time is the yield stress [21]. Viscoplastic deformation occurs in the material when the stress exceeds the yield stress. The viscoplastic deformation here is explained by the stretching, rotation, sliding and unraveling of the cross-linked chains in the polymer. However, it has been observed that there was inconspicuous strain softening in the material. As the viscoplastic deformation continues, from the yield point, resistance occurs in the material and the required load to deform the material begins to increase. At large strains, the orientation of the cross-linked chains in the material yield to a well pronounced strain hardening. Eventually, since the bonds in the epoxy are broken at high stresses, the failure occurs in the material. It is seen that failure occurs in certain strain ranges. It has been determined that this strain range for three different strain rates is between 0.36 and 0.4 mm/mm.

Table 1 exhibits the mechanical properties determined from compression tests. It is seen that as the strain rate increases, elasticity modulus values and yield strength values increase.

**Table 1** The mechanical properties of Araldite LY 564 epoxy obtained from the quasi-static compression test

| Strain rate (1/s) | Yield strength (MPa) | Elasticity modulus (MPa) | Ultimate strength (MPa) |
|---|---|---|---|
| 1.E-1 | 137 | $1987 \pm 66$ | 474 |
| 1.E-2 | 124 | $1542 \pm 99$ | 420 |
| 1.E-3 | 119 | $1465 \pm 50$ | 449 |

## High strain rate tests

By using an SHPB, high strain rate (dynamic) tests are conducted. With the SHPB method, strain rates as high as 10,000/s can be achieved. As well known, SHPB operates with a working principle of one-dimensional wave propagation. It consists of an incident bar and a transmission bar that is the same or different lengths, a shorter striker bar, and a gas gun to propel the striker bar (Fig. 2). All bars are made from the same material and have an identical cross-sectional area with each other. The material properties and the geometrical parameters of the bars that are used in this study are presented in Table 2.

The specimen is placed between the incident and transmission bars which are instrumented with strain gauges. The striker bar propelled by the gas gun hits the incident bar and generates a stress wave. This generated stress wave propagates through the incident bar to the specimen. When the wave arrived at the interface

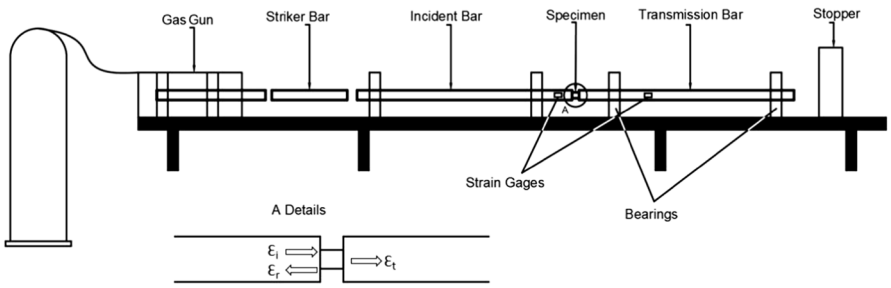



**Fig. 2** Schematic of SHPB testing setup

**Table 2** Material properties and geometric parameters of split-Hopkinson bar

| Parameters of SHPB testing | Values |
|---|---|
| Incident bar length | 2000 mm |
| Transmission bar length | 1800 mm |
| Striker bar length | 350 and 700 mm |
| The diameter of incident bar | 19.2 mm |
| The diameter of transmission bar | 19.2 mm |
| The diameter of striker bar | 19.2 mm |
| The elasticity modulus of bar materials | 180 GPa |
| The density of bar materials | 8100 kg/m$^3$ |

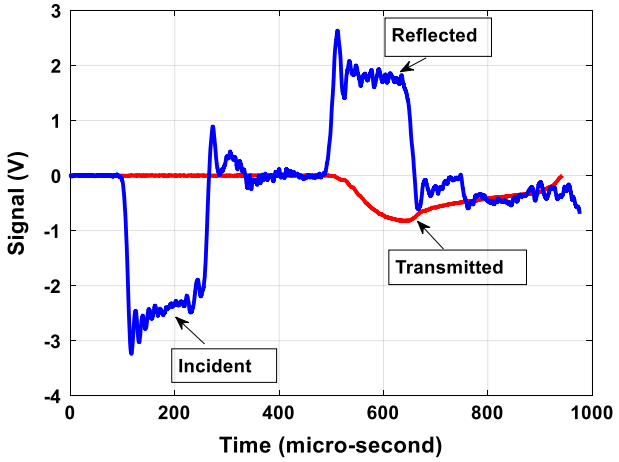



**Fig. 3** Incident, reflected and transmitted signals in SHPB testing

between the incident bar and specimen some of the waves reflected the incident bar and some transmitted to the transmission bar because of the impedance difference between bar and specimen. Strains on all three of these generated waves were measured by strain gauges. By varying the bar material, impact velocity and specimen size different strain rates can be achieved. Pulse signal recorded as a function of time using strain gauges on incident and transmission bar is given Fig. 3.

The strain gauges mounted on each bar in the form of half Wheatstone bridge, to measure only the axial strain and eliminate the effect of bending. The strain rate ($\dot{\varepsilon}$), strain ($\varepsilon$) and stress ($\sigma$) of the tested specimen in the SHPB testing were calculated using the following equations.

$$\dot{\varepsilon}(t) = \frac{-2C_0}{L_s}\varepsilon_r(t) \tag{1}$$

$$\varepsilon(t) = \frac{-2C_0}{L_s}\int_0^t \varepsilon_r(t)dt \tag{2}$$

$$\sigma(t) = \frac{E_b A_b}{A_s}\varepsilon_t(t) \tag{3}$$

The above equations are based on one-dimensional wave propagation. Where, $C_0$ is the wave velocity of the bar, $L_s$ is the length of the specimen, $A_b$and $A_s$ are the cross-section areas of bar and specimen, respectively. $E_b$ is the elasticity modulus of bar material. $\varepsilon_r$ and $\varepsilon_t$ are reflected and transmitted strains. These time-resolved strains were measured from strain gauges on the incident and transmission bar. The wave velocity of the bar, $C_0$, is calculated according to Eq. 4.

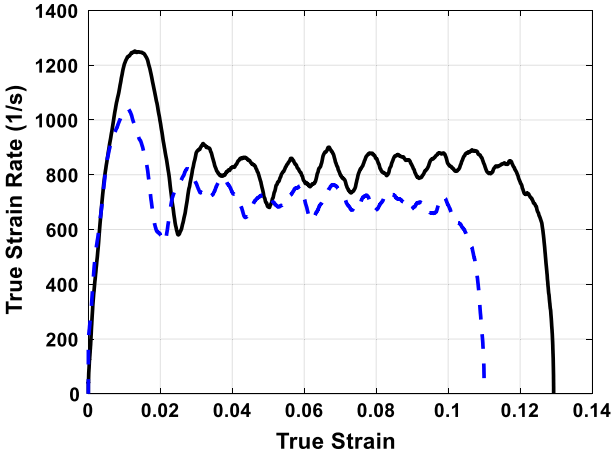



**Fig. 4** Strain rate changes of Araldite LY 564 epoxy during SHPB testing

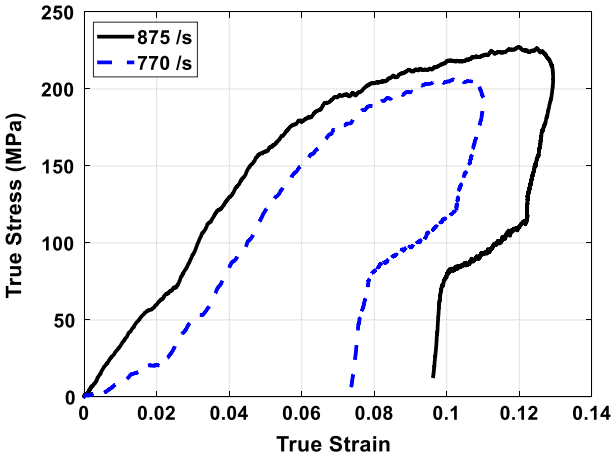



**Fig. 5** True stress–strain behaviors of Araldite LY 564 epoxy at high strain rates

$$C_0 = \sqrt{E_b/\rho} \tag{4}$$

where $\rho$ is the density of bar material. The strain rate changes of Araldite LY 564 epoxy during SHPB testing are depicted in Fig. 4. True stress–strain behaviors of Araldite LY 564 epoxy in high strain rates are shown in Fig. 5.

Average high strain rates (770 and 875/s) for the Araldite LY 564 epoxy specimen ($d = 8$ mm $L = 8$ mm) with the SHPB test process were determined according to the results shown in Fig. 4. The effect of high strain rates on the mechanical properties of the epoxy is distinctively shown in Fig. 5. Increasing strain rate increased the elasticity modulus and maximum strength of the epoxy. At high

**Table 3** The mechanical properties of Araldite LY 564 epoxy obtained from the SHPB test

| Strain rate (1/s) | Elasticity modulus (MPa) | Yield strength (MPa) | Maximum strength (MPa) |
|---|---|---|---|
| 770 | 2967 | 190 | 205 |
| 875 | 3193 | 204 | 225 |

strain rates, the movement of polymer chains is restricted. In this case, there is not enough time for the polymer chains to rearrange. With the decrease in mobility in the molecules of the epoxy chains, a high molecular resistance occurs and as a result, an increase in mechanical properties is observed. The results are summarized in Table 3.

To compare the effect of strain rate on mechanical properties, the quasi-static test result (1.E-3/s) and the SPHB test result (875/s) are shown in Fig. 6. Yield strength increased approximately 72% at high strain rate (204 MPa) compared to quasi-static loading (119 MPa). While the elasticity modulus is approximately 1.5 GPa in the quasi-static test (1.E-3/s), it is approximately 3.2 GPa at a high strain rate (875/s). In quasi-static tests (1.E-3, 1.E-2 and 1.E-1/s strain rates), the test condition is isothermal. However, at high strain rates, the test condition becomes adiabatic. In quasi-static compression, strain hardening was observed in the material but, no strain hardening occurred at high strain tests. Because of the increase in temperature occurring in adiabatic conditions, thermal softening in the material is dominant on strain hardening. In the SHPB test process, there is a shorter loading time, and therefore, the final strain value cannot be reached [4]. This situation creates an obstacle to revealing strain hardening at large strains.

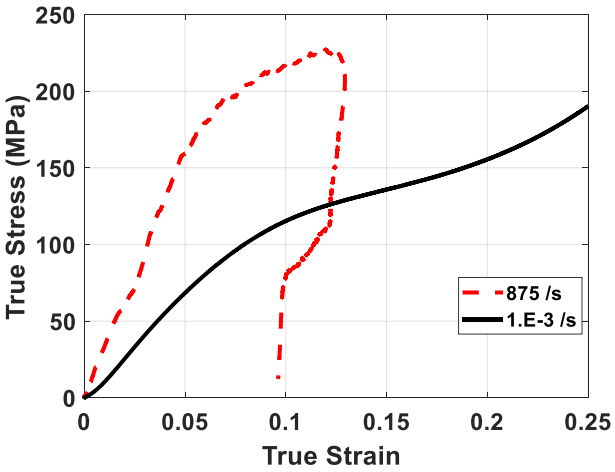



**Fig. 6** The comparison of the stress–strain response of Araldite LY564 epoxy at 1.E-3/s and 875/s strain rate

## Creep behavior

Creep tests of Araldite LY 564 epoxy were performed at approximately 35% and 70% (50 MPa and 100 MPa) of the yield point and in the stress hardening region (200 MPa) for 120 min (7200 s). The specimens are loaded to the creep stress level at 0.1/s strain rate. Creep tests aim to investigate the effect of stress level on creep behavior, and to compare creep behavior in the viscoelastic region and viscoplastic region.

True stress–strain and true strain versus time response during creep tests of Araldite LY564 are shown in Figs. 7 and 8, respectively. As shown in Fig. 7, creep strain increases the most is at 100 MPa. As expected, creep strain increases as the stress level increases. If the results of the quasi-static compression test are examined, it will be understood that this result is expected. Because 50 MPa stress level is quite far from the yield region and remains in the viscoelastic region. It has been explained previously that rate dependency is quite minimal in this region. Although 100 MPa stress level coincides just before the yield limit, it is in the region where the yield event has just begun, in other words, in the region where the material resistance under mechanical load is broken and the polymer chains are shifted to find a new equilibrium position relative to each other. Therefore, at this stress level, polymer chains displace relative to each other without much resistance. In this case, it appears to be a significant increase in strain on the macro scale. 200 MPa stress level, on the other hands, remains in the strain hardening region according to the results of the compression test described above (see Fig. 1) and coincides with the region where the material is resistant to deformation due to oriented polymer chains.

To observe the primary creep clearly, true strain versus time curves for three different stress levels is plotted up to 100 s. and depicted in Fig. 9.

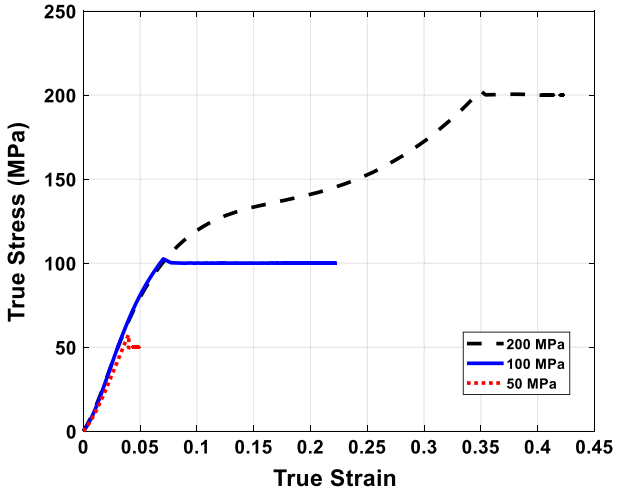



**Fig. 7** True stress–true strain curve for creep test performed at three different stress levels (50,100 and 200 MPa)

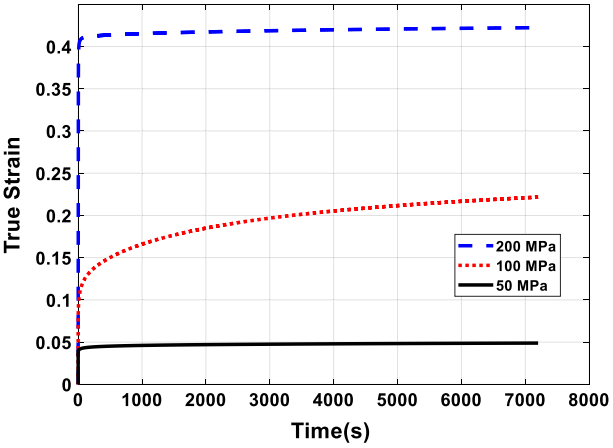



**Fig. 8** True strain versus time response for creep tests performed at three different stress levels (50, 100 and 200 MPa)

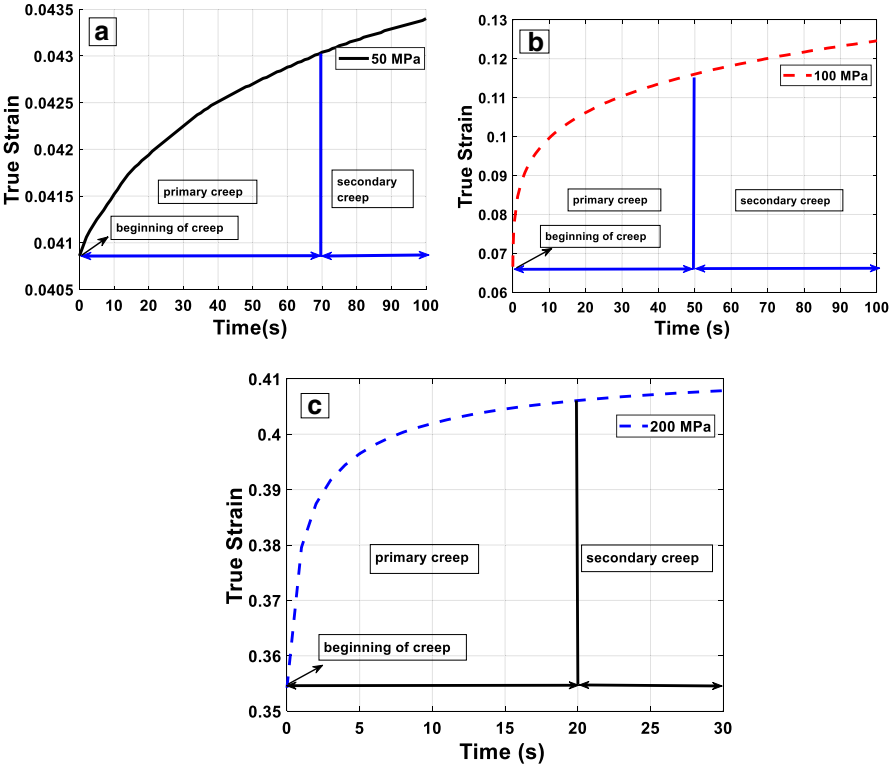



**Fig. 9** True strain for time response for **a** 50 MPa, **b** 100 MPa, **c** 200 MPa constant stress levels

Creep compliance is an important material property to determine the stress–strain relationship of materials that exhibit viscoelastic behavior like in polymers. Creep compliance is defined as the ratio of strain to constant stress as a function of time. Creep compliance (J(t)) is calculated according to Eq. 5.

$$J(t) = \frac{\varepsilon(t)}{\sigma_0} \tag{5}$$

where $\varepsilon(t)$ and $\sigma_0$ are time-dependent strain and constant stress at a given strain, respectively.

Creep compliance is used to determine material parameters in viscoelastic material models (linear viscoelastic + nonlinear viscoelasticity) used in finite element analysis. The rheological behavior of polymeric materials can be characterized by creep compliance, which is a material feature [22]. In this study, creep compliance versus time relation was demonstrated to determine the material behavior of Araldite LY564 epoxy in viscoelastic and viscoplastic regions. Creep compliance versus time response for creep tests of Araldite LY564 is shown in Fig. 10.

Creep compliance is given in Fig. 10. As expected, the compliance curves follow the same trend with true strain/time figure given in Fig. 8. The commercial FEM solvers require creep compliance values to define the creep behavior of viscoelastic materials, and therefore, these values are reported in this work in addition to creep test results.

## Relaxation tests

Relaxation tests were performed at 3.16, 7.15 and 35.5% strain levels for 120 min (7200 s). These strain levels correspond to the stress levels where creep tests are

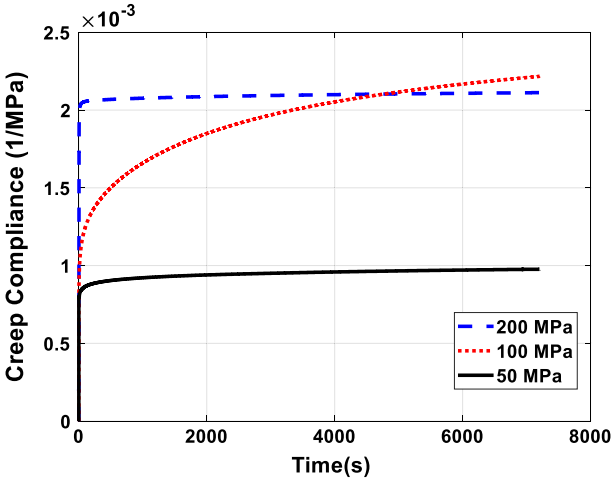



**Fig. 10** Creep compliance versus time response for creep tests of Araldite LY564 epoxy for three different stress levels

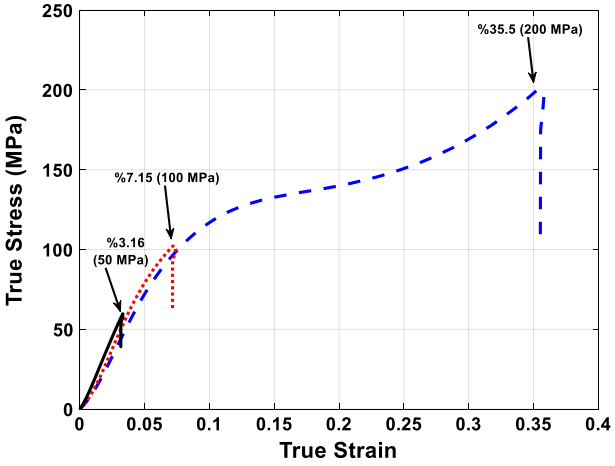



**Fig. 11** True stress–true strain curves for relaxation tests performed at three different strain levels

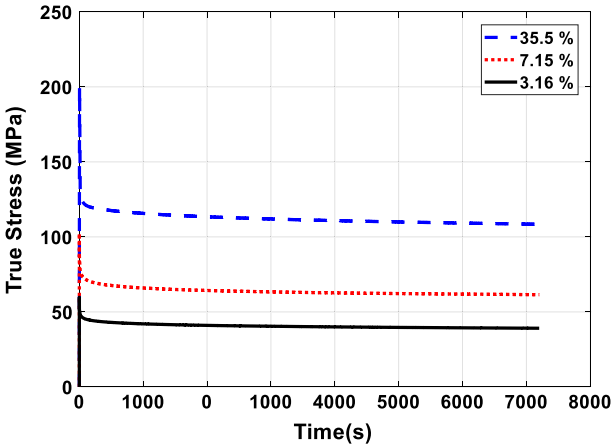



**Fig. 12** True strain versus time response for relaxation tests performed at three different strain levels

performed. The relaxation tests aim to reveal the effect of the strain level on the relaxation behavior of the Araldite LY 564 epoxy. Although stress relaxation is insignificant at the low strain in metallic materials, relaxation is observed in polymeric materials even at the smallest strain levels [23], [20]. Stress relaxation describes how polymers relieve stress under constant strain as they are viscoelastic materials. True stress–strain and true strain versus time response for relaxation tests of Araldite LY564 are presented in Figs. 11 and 12, respectively.

As shown in Fig. 11, the most stress drop occurred at a strain level of 35.5%, loaded up to a stress level of 200 MPa. This is followed by a strain level of 7.16% and 3.15%, which corresponds to a stress level of 100 MPa and 50 MPa, respectively. As expected, as the strain level increases, so do the stress drop. The strain

level of 3.15% remains in the elastic region and the least stress drop is observed here because, as mentioned previously, rate dependency is quite minimal in this region. Since the stress level of 50 MPa is lower than the yield point of the material, the instantaneous drop is a result of elastic deformation. However, it takes time for the polymer chains in the material to return to their initial position. In Fig. 1, it is observed that at these strain levels, the material exhibits a mechanical behavior dependent on strain rate and time. As the strain level increased, dependency on the strain rate increased and higher stress drops were seen. In Table 4, the details of the relaxation results which are shown in Fig. 12 are given. According to Table 4, the increase in the strain level is proportional to the increase in the stress drop.

Finite element analysis of structural elements using various software has been extensively used in design and optimization. The selection of a proper material model is very important in these analyses. In finite element analysis of polymeric materials, it is necessary to define various material parameters to these models to determine the viscoelastic and viscoplastic behavior of the material. In this context, the material parameters required for the material models used to determine the behavior of the Araldite LY564 epoxy material can be identified by the change of relaxation modulus versus time. The relaxation modulus is defined as the ratio of stress to the constant strain level. Relaxation modulus (G(t)) is calculated according to Eq. 6.

$$G(t) = \frac{\sigma(t)}{\varepsilon_0} \tag{6}$$

where $\sigma(t)$ and $\varepsilon_0$ are time-dependent stress and constant strain at given stress, respectively.

The response of relaxation modulus versus time is shown in Fig. 13. It is seen that as the strain level increases, the change in the relaxation modulus increases with time.

## Conclusions

The mechanical characterization of Araldite LY564 epoxy at quasi-static and high strain rates is done. In addition to quasi-static compression and SHPB tests, to complete the viscoelastic, viscoplastic indications of the polymer, creep and relaxation tests are also performed. The creep behavior for three different stress values and

**Table 4** Details of relaxation results

| Constant strain level (%) | Corresponding stress level (MPa) | Stress at the end of the test (MPa) | Stress drop (%) |
|---|---|---|---|
| 3.16 | 50 | 39 | 22 |
| 7.15 | 100 | 61 | 39 |
| 35.5 | 200 | 109 | 45.5 |

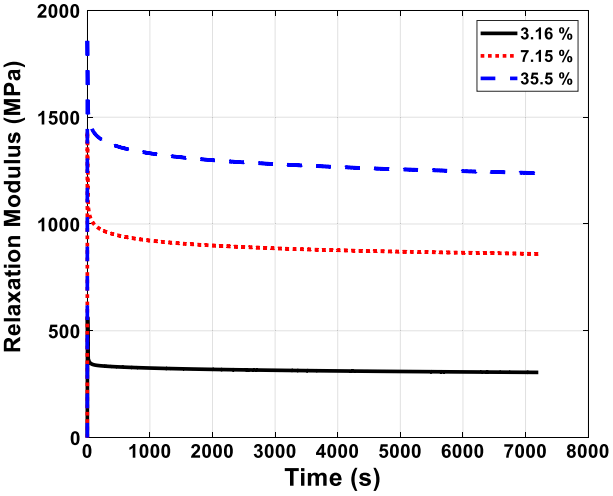



**Fig. 13** Relaxation modulus versus time response Araldite LY564 epoxy at different strain levels

relaxation behavior for three different strain values are investigated. Therefore, a comprehensive viscoelastic–viscoplastic characterization is achieved.

Quasi-static compression tests performed at 1.E-3, 1.E-2 and 1.E-1/s strain rates reveal that the mechanical properties (elasticity modulus, yield strength) increase as the strain rate increases. SHPB is used to investigate the high strain rate behavior of Araldite LY564 epoxy at two different strain levels, (770 and 875/s). In the SHPB test, a 118% increase in elasticity modulus and 72% increase in yield strength are observed compared to quasi-static loading.

More prominent creep behavior is observed for stress levels close to the yield stress. With increasing strain levels, the stress drop during relaxation increases. The commercial FEM solvers use creep compliance and relaxation modulus as parameters to define the viscoelastic properties of the materials. Therefore, these values are calculated and reported in addition to strain/time and strain/time results.

It is planned to investigate the effect of graphene as a reinforcing agent, on the viscoelastic and viscoplastic behavior of epoxy material. Besides, a viscoelastic—viscoplastic material model that is capable of predicting the time and temperature-dependent mechanical behavior of epoxy and its nanocomposites for quasi-static and dynamic loads is planned to be developed.

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## References

1. Jin F-L, Li X, Park S-J (2015) Synthesis and application of epoxy resins: a review. J Ind Eng Chem 29:1–11. https://doi.org/10.1016/j.jiec.2015.03.026
2. Shadlou S, Ahmadi-Moghadam B, Taheri F (2014) The effect of strain-rate on the tensile and compressive behavior of graphene reinforced epoxy/nanocomposites. Mater Des 59:439–447. https://doi.org/10.1016/j.matdes.2014.03.020

3. Tamrakar S, Ganesh R, Sockalingam S et al (2018) Experimental investigation of strain rate and temperature dependent response of an epoxy resin undergoing large deformation. J Dyn Behav Mater 4:114–128. https://doi.org/10.1007/s40870-018-0144-8
4. Jordan JL, Foley JR, Siviour CR (2008) Mechanical properties of Epon 826/DEA epoxy. Mech Time-Depend Mater 12:249–272. https://doi.org/10.1007/s11043-008-9061-x
5. Colak ÖU, Bahlouli N, Uzunsoy D, Francart C (2020) High strain rate behavior of graphene-epoxy nanocomposites. Polym Test 81:106219. https://doi.org/10.1016/j.polymertesting.2019.106219
6. Goglio L, Peroni M, Rossetto M (2007) Effect of the strain rate on the mechanical behaviour of epoxy adhesives. Key Eng Mater 347:671–676. https://doi.org/10.4028/www.scientific.net/KEM.347.671
7. Gilat A, Goldberg RK, Roberts GD (2002) Experimental study of strain-rate-dependent behavior of carbon/epoxy composite. Compos Sci Technol 62:1469–1476. https://doi.org/10.1016/S0266-3538(02)00100-8
8. Tay TE, Ang HG, Shim VPW (1995) An empirical strain rate-dependent constitutive relationship for glass-fibre reinforced epoxy and pure epoxy. Compos Struct 33:201–210. https://doi.org/10.1016/0263-8223(95)00116-6
9. Littell JD, Ruggeri CR, Goldberg RK et al (2008) Measurement of epoxy resin tension, compression, and shear stress-strain curves over a wide range of strain rates using small test specimens. J Aerosp Eng 21:162–173. https://doi.org/10.1061/(ASCE)0893-1321(2008)21:3(162)
10. Mayr AE, Cook WD, Edward GH (1998) Yielding behaviour in model epoxy thermosets—I. Effect of strain rate and composition. Polymer 39:3719–3724. https://doi.org/10.1016/S0032-3861(97)10334-2
11. Li P, Petrinic N, Siviour CR et al (2009) Strain rate dependent compressive properties of glass microballoon epoxy syntactic foams. Mater Sci Eng A 515:19–25. https://doi.org/10.1016/j.msea.2009.02.015
12. Theocaris PS (1962) Viscoelastic properties of epoxy resins derived from creep and relaxation tests at different temperatures. Rheol Acta 2:92–96. https://doi.org/10.1007/BF01972534
13. Lee A, Mckenna GB (1998) Anomalous aging in two-phase systems: Creep and stress relaxation differences in rubber-toughened epoxies. J Polymer Sci Part I Polymer Phy 35:1167–1174. https://doi.org/10.1002/(SICI)1099-0488(199706)35:8<1167::AID-POLB1>3.0.CO;2-R
14. Ornaghi HL Jr, Neves RM, Monticeli FM, Almeida JHS Jr (2020) Viscoelastic characteristics of carbon fiber-reinforced epoxy filament wound laminates. Compos Commun 21:100418. https://doi.org/10.1016/j.coco.2020.100418
15. Almeida HS Jr, Ornaghi HL Jr, Amico SC (2017) Creep and interfacial behavior of carbon fiber reinforced epoxy filament wound laminates. Polym Compos 39:8. https://doi.org/10.1002/pc.24537
16. Almeida JH, Ornaghi HL, Lorandi N et al (2018) On creep, recovery, and stress relaxation of carbon fiber-reinforced epoxy filament wound composites. Polym Eng Sci 58:1837–1842. https://doi.org/10.1002/pen.24790
17. Nosrati N, Zabett A, Sahebian S (2020) Long-term creep behaviour of E-glass/epoxy composite: time-temperature superposition principle. Plast Rubber Compos 49:254–262. https://doi.org/10.1080/14658011.2020.1736867
18. Huntsman datasheet
19. Wang R-M, Zheng S-R, Zheng Y-P (2011) Polymer matrix composites and technology. Woodhead Publishing Limited, Sawston
20. Olowojoba GB, Eslava S, Gutierrez ES et al (2016) In situ thermally reduced graphene oxide/epoxy composites: thermal and mechanical properties. Appl Nanosci 6:1015–1022. https://doi.org/10.1007/s13204-016-0518-y
21. Wang F, Drzal LT, Qin Y, Huang Z (2015) Mechanical properties and thermal conductivity of graphene nanoplatelet/epoxy composites. J Mater Sci 50:1082–1093. https://doi.org/10.1007/s10853-014-8665-6
22. Kim J, Sholar GA, Kim S (2008) Determination of accurate creep compliance and relaxation modulus at a single temperature for viscoelastic solids. J Mater Civ Eng 20:147–156. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:2(147)
23. Dusunceli N, Colak OU (2008) The effects of manufacturing techniques on viscoelastic and viscoplastic behavior of high density polyethylene (HDPE). Mater Des 29:1117–1124. https://doi.org/10.1016/j.matdes.2007.06.003


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