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Punch indentation of polyurea at different loading velocities: Experiments and numerical simulations

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Punch indentation experiments are performed on 10 mm thick polyurea layers on a steel substrate. A total of six different combinations of punch velocity, punch size and the lateral constraint conditions are considered. Furthermore, the time integration scheme for a newly-developed rate-dependent constitutive material model is presented and used to predict the force–displacement response for all experimental loading conditions. The comparison of the simulations and the experimental results reveals that the model is capable to predict the loading behavior with good accuracy for all experiments which is seen as a partial validation of the model assumptions regarding the pressure and rate sensitivity. As far as the unloading behavior is concerned, the model predicts the characteristic stiff and soft phases of unloading. However, the comparison of simulations and experiments also indicates that the overall model response is too stiff. The results from cyclic compression experiments suggest that the pronounced Mullins effect needs to be taken into account in future models for polyurea to improve the quantitative predictions during unloading.

1. Introduction

Polyurea is a highly viscoelastic rubber material that is used for the impact protection of vehicle structures. It is considered for the armor protection and retrofitting of military vehicles that are exposed to the blast loading of improvised explosive devices. The anticipated effect of polyurea coatings on the blast resistance of steel plates is twofold. Firstly, the polyurea can directly absorb a portion of the blast energy as it undergoes large deformations. Secondly, the onset of ductile fracture of a steel plate may be retarded through the use of a polyurea coating, thereby increasing the energy absorption of the steel structure. The amount of energy dissipation through polyurea coating is relating to the hysteresis area of the stress–strain curve under loading–unloading conditions. Recent experimental results (e.g. Ayoub et al., 2009) reported that some elastomers show asymmetric rate-sensitivity, i.e. strong rate-sensitivity during loading but weak rate-sensitivity during unloading. Thus, the proper prediction of unloading behavior is important to obtain a good estimation of the amount of energy dissipation.

As discussed by Xue and Hutchinson (2008), necking occurs under uniaxial tension when the average true stress becomes equal to the overall tangent hardening modulus (Considere criterion). In the case of a coated ductile substrate, a high strain hardening coating material can increase the effective hardening modulus of the bilayer material such that necking is retarded with respect to the Considere strain of the uncoated material. The bifurcation analysis of Guduru et al. (2006) reveals that an added surface layer can increase the resistance of a structural element to fragmentation. Moreover, their results show that the addition of a soft coating with high strain hardening can improve the weight specific energy absorption of the

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structural element. Xue and Hutchinson (2008) demonstrate that the ratio of the elastomer modulus to the flow strength of the substrate controls the effect of necking retardation. McShane et al. (2008) performed tension and bulge tests on copper/polyurethane bilayers under static and dynamic conditions. Their experimental measurements indicate that coatings do not provide dynamic performance benefits on an equal mass basis. While the total blast resistance increases, the weight specific energy absorption of the structure may actually decrease through the application of a polymer coating. Dynamic ring expansion experiments have been performed by Zhang et al. (2009) on polyurea coated aluminum 6061-O and copper 101 at very high strain rates (4000–15,000/s). Their experimental results show that there is no significant effect of the polyurea coating on the strain at the onset of localization.

It appears that the neck retardation effect in coated ductile substrates is difficult to achieve when using polyurea in combination with typical engineering materials. However, as pointed out by McShane et al. (2008), polyurea coatings may still be seen as a practical solution for enhancing the blast resistance of metallic structures because of the ease of applying polyurea on existing structures (retrofitting). Even though the performance of the steel substrate may remain unaffected, a very thick polyurea layer can still increase the energy absorption in absolute terms. The impulsive loading experiments of Amini et al. (2010c) reveal that polyurea coatings have a strong effect on the energy transfer to the steel plate. In particular, they demonstrate that the positioning of polyurea on the impact side promotes failure of the steel plate under shock loading while a polyurea layer on the back of the plate attenuates the shock. In the present paper, we deal with the prediction of the large deformation behavior of polyurea in structural applications. Xue and Hutchinson (2008) made use of a Moonley–Rivlin model for the polymer coating in their numerical analysis of the polymer/metal bilayers. Zhang et al. (2009) modeled the behavior of polyurea using a non-linear hyperelastic material model. However, both uniaxial compression and tension tests have demonstrated that the mechanical response of polyurea is highly strain-rate dependent (e.g. Amirkhizi et al., 2006; Roland et al., 2007; Sarva et al., 2007; Shim and Mohr, 2009). Amini et al. (2010d) make use of the temperature-, rate- and pressure-sensitive constitutive model by Amirkhizi et al. (2006) to provide supporting simulation results of their direct pressure pulse experiments. They also recently reported the effect of asymmetric tension–compression response and the hydrostatic pressure on the blast resistance of polyurea/steel plates (Amini et al., 2010a, 2010b).

Finite viscoelasticity models of elastomers may be formulated using the so-called hereditary integral approach (Coleman and Noll, 1961; Bernstein et al., 1963; Lianis, 1963; McGuirt and Lianis, 1970; Leonov, 1976; Johnson et al., 1994; Haupt and Lion, 2002; Amirkhizi et al., 2006) but their validity is often limited to a narrow range of strain rates (Yang et al., 2000; Shim et al., 2004; Hoo Fatt and Ouyang, 2007). As an alternative to the hereditary integral approach, the framework of multiplicative decomposition of the deformation gradient (Kröner, 1960; Lee, 1969) is frequently used in finite viscoelasticity (e.g. Sidoroff, 1974; Lubliner, 1985; Le Tallec et al., 1993; Reese and Govindjee, 1998; Huber and Tsakmakis, 2000). In that framework, the non-linear viscoelasticity of elastomers is commonly described through a rheological spring-dashpot models of the Zener type (e.g. Roland, 1989; Johnson et al., 1995; Bergström and Boyce, 1998; Huber and Tsakmakis, 2000; Quintavalla and Johnson, 2004; Bergström and Hilbert, 2005; Qi and Boyce, 2005; Areias and Matous, 2008; Hoo Fatt and Ouyang, 2008; Tomita et al., 2008).

For the coating applications to blast and ballistic mitigations, the hydrostatic pressure and temperature as well as strain rates play a critical role to determine the mechanical properties of the polyurea under the loading. It is known that two different types of viscoelastic behavial modes are observed in polymeric materials including polyurea: global chain mode responsible for rubbery and flow properties and local segmental mode responsible for behavior below glass transition temperature (e.g. Roland and Casalini, 2007). The temperature–pressure dependences are strongly influenced by those viscoelastic modes, however, very limited experimental studies have been reported on the effect of pressure and temperature (Amirkhizi et al., 2006; Roland and Casalini, 2007; Roland et al., 2010). Although the universal constitutive model for polyurea should include all the effects, the proposed model in the paper, as the first engineering approach, considers only the effect of strain rates for the rubbery viscoelastic behavior. In the present work, we present the time integration scheme for a newly developed rate-dependent constitutive model for polyurea (Shim and Mohr, 2011). After implementing the model as a user material subroutine into a commercial finite element software, the model is used to predict the mechanical response of thick polyurea layers under punch loading. Experiments are performed on 10 mm thick polyurea layers for different punch velocities and different hemispherical punch radii. It is found that the model provides an accurate description of the loading phase, which validates the assumptions made with respect to strain-rate and pressure sensitivity. However, the predicted response deviates from the experimental result during unloading which is discussed in detail.

2. Punch experiments

2.1. Specimens

The polyurea specimens used in the study are extracted from a 5 mm thick steel armor plate with a 12.7 mm thick layer of polyurea DragonShield-HT Explosive Resistant Coating (ERC). Rectangular samples of 46×40 mm are cut from the coated armor plate using conventional machining. The coated polyurea is not separated from the steel as the steel substrate serves as specimen support throughout the punching experiments. However, to guarantee a uniform layer thickness for all specimens, the thickness of the polyurea layer is reduced to 10 mm though conventional machining (milling at room