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Nonlinear Behavior of a Medium Density Polyethylene Pipe Material

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Abstract: Medium density polyethylene (MDPE) pipes are extensively used for gas distribution system in Canada and worldwide. MDPE pipe material possesses time-dependent behavior that governs the performance of the pipes in air or buried in the soil. However, very limited information is currently available in the literature on the time-dependent behavior of MDPE pipe materials. In this research, an extensive laboratory investigation is carried out to investigate the time-dependent behavior of MDPE pipe material. Uniaxial tensile tests are conducted with samples (coupons) cut from the wall of a 60 mm diameter MDPE pipe using waterjet. A surface planer has been used to remove the curvature. The coupon samples cut from the pipe might experience residual stresses during sample preparation, which might affect the test results. To investigate the effect of the residual stresses, tensile tests with samples of full cross-section of the pipe are also conducted. Tests are conducted at various strain rates to capture the effects of loading rates. The experimental results are used to develop numerical modelling approach for time-dependent material behaviour using a commercially available software, Abaqus. The strain-rate dependent material behavior of MDPE is incorporated in Abaqus through development of USDFLD subroutine. The proposed modeling approach successfully simulates the test results of the MDPE pipe. Temperature effects on the mechanical behavior of MDPE pipe were not considered.

1 INTRODUCTION

Many of today's plastics were developed during and just before World War II. Since then plastic pipe usage has increased at a significantly high rate due to its various advantages over metal pipes including low cost, light-weights, ease of installation and corrosion resistance. Water supply, cold water distribution, sewer, gas distribution and irrigation are the major areas of application of plastic pipes. Plastic pipes are divided into two groups: thermoset and thermoplastic. Usage of medium density polyethylene (MDPE) pipe, a thermoplastic material, is rapidly increasing due to its good shock and drop resistance properties.

The buried distribution pipes are subjected to loads from the weight of the soil column above the pipe, the surcharge loads including live traffic and dead load, internal pressure and loads from ground movement resulting from seismic activities. Generally, soil-pipe interaction analysis is performed to understand the behaviour of pipes under aforementioned loads. However, modelling of soil-pipe interaction for polyethylene pipes is complex as the behaviour of polymer material is time, temperature and strain rate dependent. Numerous attempts have been made for investigating the nonlinear time-dependent behaviour of polyethylene pipe materials with particular attention to High Density Polyethylene (HDPE) pipes. Earlier work focused on developing relaxation modulus used for calculating the time-dependent responses under a fixed stress. The modulus of elasticity of pipe material at a particular stress level is expressed using a power law relation of time (chua and Lytton 1989). Moore (1994) developed a linear viscoelastic model using nine kelvin elements in series for describing the viscous effects of a HDPE pipe material. Although the linear viscoelastic model successfully simulated stress–strain responses at lower strains, the model was unsuccessful at the higher strains. A non-linear viscoelastic and viscoplastic modelling approaches are then employed to reasonably simulate the stress–strain behaviour under various loading conditions (Zhang and Moore 1997, Chehab and Moore 2006). Siddquee and Dhar (2015) developed a strain-rate dependent nonlinear three-component elastic viscoplastic model for a HDPE pipe material. However, very limited information is currently available on the study of MDPE pipe materials. Ben-Hadz-Hamouda et al. (2007) conducted an experimental investigation of a type of MDPE and demonstrated extensive strain rate effects on the material behaviour. The objective of the current study is to investigate the time-dependent behaviour of MDPE pipe material for pipe-soil interaction analysis. Muntakim et al (2018) have simulated the time dependent behavior of buried HDPE pipe using a commercially available finite element (FE) software, Abaqus (Dassault Systems 2015). This approach is employed here to simulate the time dependent behaviour of MDPE pipe material.

This study includes two components: 1) experimental investigation for identifying the nonlinear strain rate dependent behavior of MDPE in tension; 2) Development of a numerical modelling approach to simulate the strain rate dependent behaviour of MDPE pipe. The experimental results and the corresponding model predictions are reported in this paper. The capability of the modelling approach is evaluated through the simulation of rate-dependent stress–strain response.

2 SPECIMEN PREPARATION AND EXPERIMENTAL SETUP

To examine the strength and deformation behaviour of a MDPE material, several tensile tests were conducted in the structure lab at Memorial University of Newfoundland, Canada. All the tensile tests in this paper were performed on coupons, cut from the wall of a 60.3 mm diameter and 5.5 mm thick MDPE pipe. The samples were prepared according to ASTM D638-14 specifications. Water jet was used for cutting the tensile coupons and a surface planer was used to remove the curvature. The length of the test specimens was parallel to the length of the MDPE pipe. The INSTRON (5585H) machine was used to apply loads to the test specimens through moving the crosshead of the machine. The upward movement of the crosshead causes a tensile load and downward movement causes a compressive load on the specimens. A load transducer which is mounted in series with the specimen measures the applied load and converts the load into an electrical signal that a control system measures and displays. A strain transducer (extensometer) was also used on this system to measure strain. The testing system was controlled using an Instron proprietary software. Figure 1 shows the experimental set up of the tensile coupon tests.

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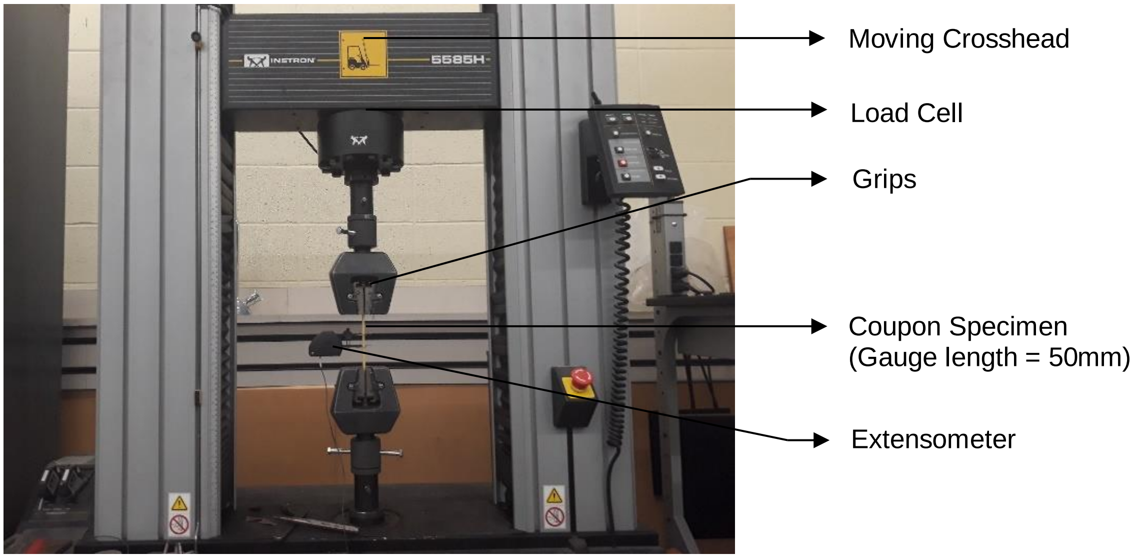

Figure 1: Test set up and loading apparatus for coupon test.

The change of the height of the specimen was measured by recording the ram position through the displacement transducer of the Instron machine and the corresponding loads were measured by the load cell. A computer controlled system was used to monitor and record the outputs of the displacement transducer and the load cell. A tensile test with full pipe cross-section of MDPE pipe was also conducted to see whether the cutting of samples might affect the test result or not. Figure 2 shows the experimental set up of full pipe tensile test.

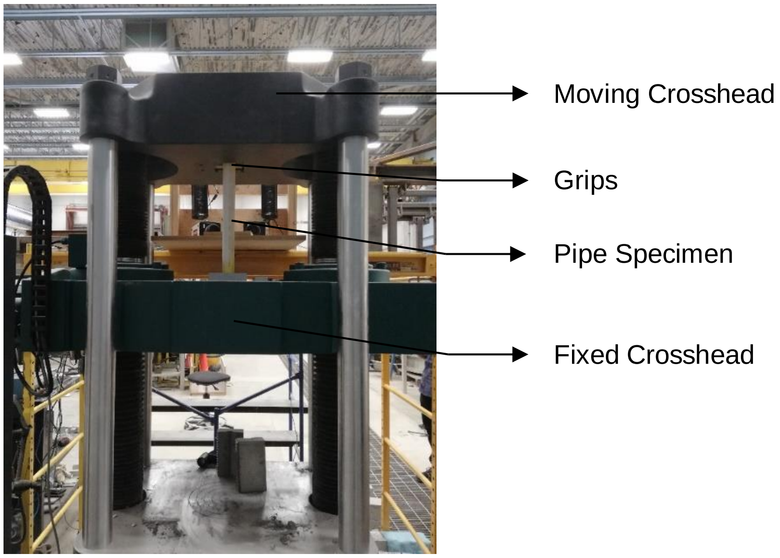

Figure 2: Test set up and loading apparatus for full pipe test.

2.1 Test Results

To understand the effect of the rate of loading, four uniaxial tension tests were conducted at constant strain rates ranging from 10^{-5} /s to 10^{-2} /s. A test range was selected for each test to avoid necking. The highest range for measuring the strain was 0.14 (mm/mm). The results are shown in Figure 3. From Figure 3, it is evident that the stress–strain relationship of the MDPE pipe is highly strain rate dependent.

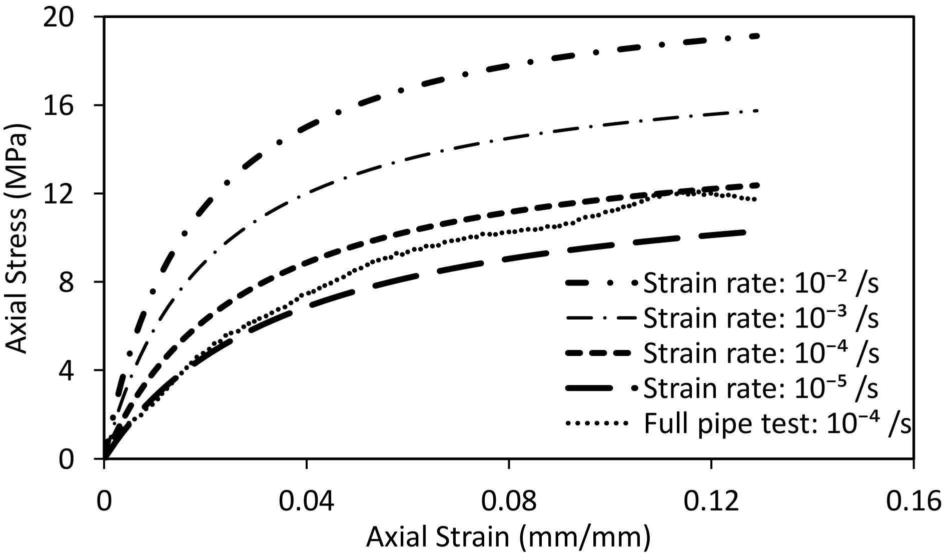

Figure 3: Experimental results for constant strain rate.

Initially, the stress increases almost linearly with the strain, but the relationship quickly becomes nonlinear. Within the test range, there are no peak stresses found on the stress–strain curve. This figure also shows the result of stress–strain response conducted for the full pipe test. A strain rate of 10^{-4} /s was used for this test. It initially underestimates the coupon test results because slipping at the grips occurred initially, however, at higher load it matches with the coupon test results conducted at the same strain rate (10^{-4} /s). Thus, the coupon test results reasonably represent the mechanical behaviour of the pipe.

To see the strain-rate history dependency of MDPE pipe material, a strain rate jump test was implemented. Initially, a strain rate 10^{-3} /s was applied up to a strain of 0.065. After that the rate was changed from 10^{-3} /s to 10^{-2} /s and then back to the previous rate at axial strain 0.11 (mm/mm). The results are shown in Figure 4 along with the stress–strain responses corresponding to the strain rates of 10^{-3} /s and 10^{-2} /s, respectively. As seen in the figure, at the change of the strain rate to 10^{-2} /s from 10^{-3} /s, a gradual increase of stress occurred. After increasing of rapid stress within a short period, the stress reached to the level it would have held if the new strain rate, i.e. 10^{-2} /s, had been used from the beginning of the test (matches with the stress–strain response for the strain rate of 10^{-2} /s). Similarly, with the change of the strain back to 10^{-3} /s, the response follows the stress–strain response corresponding to 10^{-3} /s strain rate with a sudden drop. Similar responses were reported earlier for High Density Polyethylene (HDPE) in Zhang and Moore (1997). Therefore, the stress–strain responses of the MDPE do not have strain-rate history dependency, but follow the strain-rate dependent stress–strain relations.

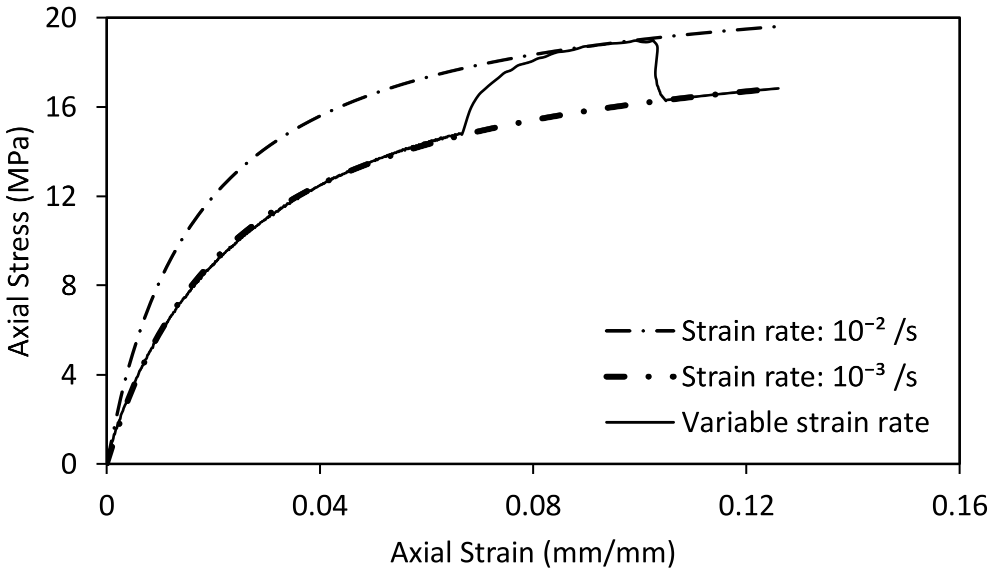

Figure 4: Experimental result for strain rate jump test.

A cyclic loading test was also performed to see the loading-unloading-reloading behavior of the MDPE pipe. Figure 5 shows the results of the cyclic loading test. The test was conducted at the same magnitude of strain rate 10^{-3} /s during the load-unload-reload cycle. The stress–strain curve for reloading gradually approached the monotonic loading curve.

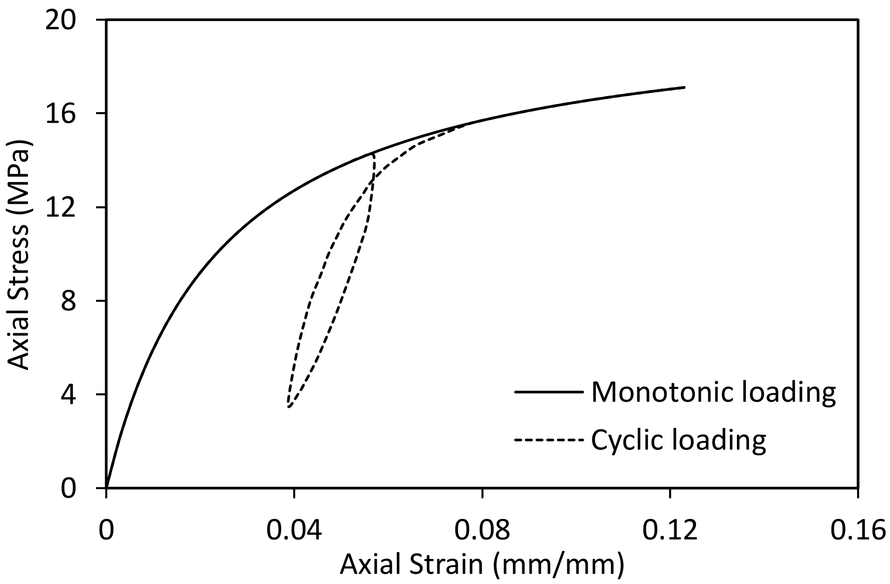

Figure 5: Experimental result for cyclic loading test (Strain rate: 10^{-3}/s)

3 MODELLING OF TIME-DEPENDENT RESPONSES

A number of different constitutive models were developed to capture the nonlinear time-dependent behavior of HDPE materials (Chua and Lytton 1989, Zhang and Moore 1997, Chehab and Moore 2006, Suleiman and Coree 2004, Siddiquee and Dhar 2015). However, none of these models are implemented in commercially available finite element (FE) software. As a result, the models are not widely used for analysing engineering problems. Muntakim et al (2018) employed the features available in a commercially available FE software, Abaqus (Dassult system 2015) to simulate the time-dependent behaviour of a HDPE pipe material. The technique used in Muntakim et al (2018) is employed here for modelling the time-dependent behaviour of MDPE pipe material. Tensile and/ or compression tests are generally performed with the application of different rates of loading to investigate the time dependent response of material. Strain rate dependent stress–strain relationships are used to simulate the time-dependent response. These data are implemented using user subroutine, USDFLD, in Abaqus. USDFLD allows defining field variables at a material point as a function of time or solution dependent material properties. It provides access to material point quantities at the start of the increment and gives explicit solution. In this process, the material properties are not influenced by the results obtained during the increment. So, the accuracy depends on the size of the time increment and this time increment can be controlled by the variable PNEWDT (Dassult Systems 2015). At the start of the increment, a utility routine, GETVRM, is used to access the material point. By calling GETVRM with the appropriate output variable keys, the values of the material point quantities are obtained. ARRAY, JARRAY, FLGRAY are used to recover the values of material point data (the floating point, integer and character data). At each increment, the field variables are restored to the values interpolated from the nodal values and introduced with user defined state variables, STATEV, which can be recalled using variable key ‘SDV’ in the utility routine, GETVRM.

In this study, GETVRM is used to access all the strain components. User-defined state variables are assigned to store current strain component, time increment and the calculated strain rate for using in subsequent time steps. The strain rate is calculated based on the current strain (accessed by the GETVRM), the previous strain (stored in user defined variables) and time increment (accessed by USDFLD).

FIELD variable, which is an array containing field variables at the current material point, is used to assign the strain rate. On the basis of the information of these FIELD variables given in the input file, Abaqus interpolates the material parameters. In this interpolation, an average value is used for linear elements and an approximate linear variation is used for quadratic elements.

The strain rate dependent stress–strain responses of MDPE pipe were found in experimental investigation. These test data were given in Abaqus input file for modelling of time-dependent behaviour of MDPE pipe using the feature in Abaqus. On the basis of these test data and FIELD variable from USDFLD, Abaqus uses its default constitutive model to calculate Jacobian matrix and stress and other parameters.

3.1 FE Simulation of Test Results

Finite element analysis was performed for numerical simulations of the uniaxial tension tests carried out. As discussed earlier, tension tests were conducted using coupon specimens of 13 mm width (width of the narrow section) and 50 mm gauge length. The tests were performed with the application of constant strain rates ranging from 10^{-5} /s to 10^{-2} /s. These strain-rate dependent stress–strain data were given in the input file and simulated using FE modelling using Abaqus. In the FE analysis, the same size of the specimen was used. Smooth rigid boundaries were used at the bottom and the left side. Figure 6 shows the FE mesh. The horizontal and vertical translations were restrained at the corner node. At the top of the mesh, a uniform strain was applied at the same rates as those applied during the tension tests.

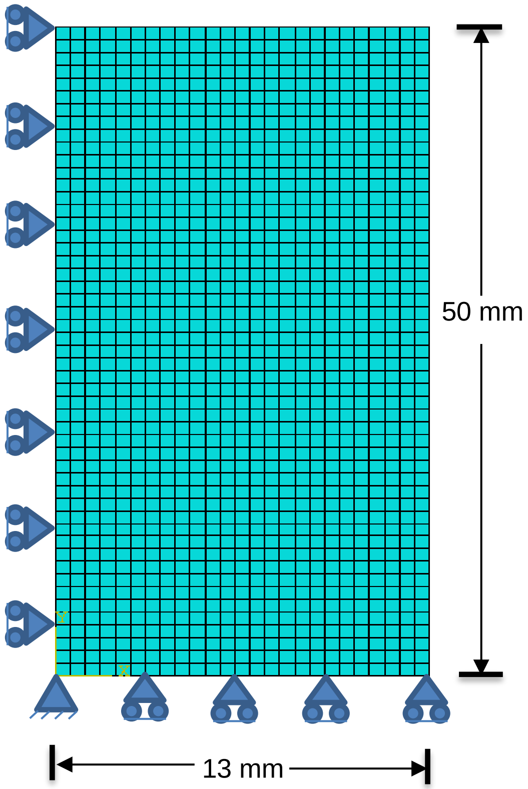

Figure 6: FE model

3.2 Comparison of Results

The stress–strain relationships obtained from the finite element analysis and experimental investigation are shown in Figure 7. A reasonable agreement appears between the simulated and experimental curves in the figure. Thus, the method employed is capable of predicting the time dependent stress–strain behaviour of the MDPE material.

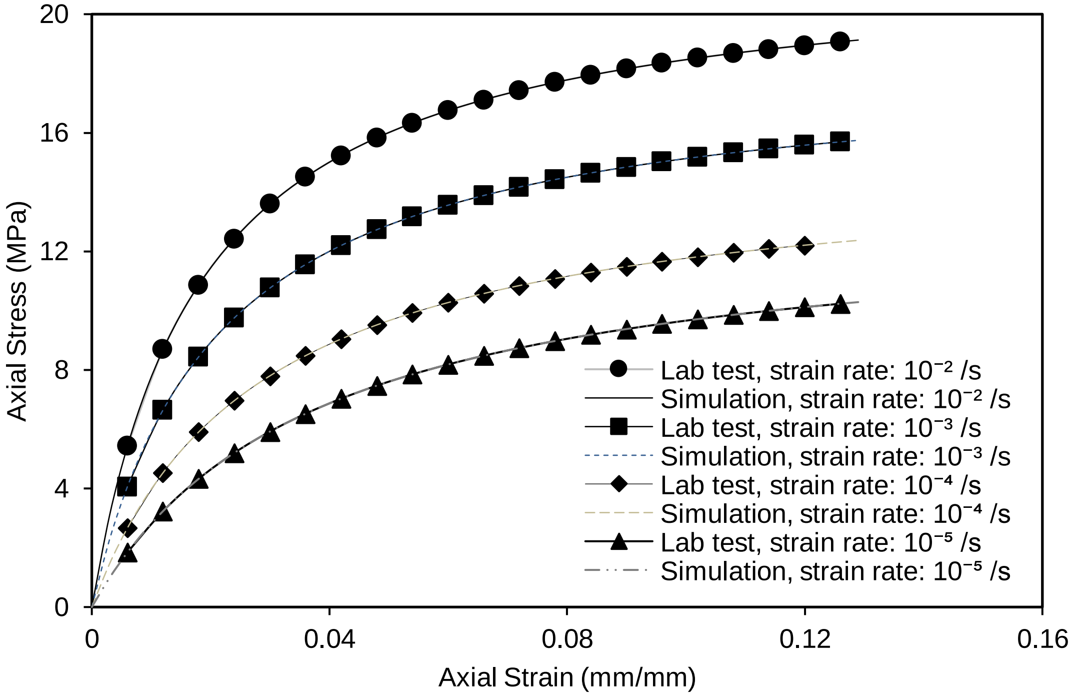

Figure 7: Comparison of test results with finite element analysis.

A strain rate jump test performed during the experimental tests is also successfully simulated by this method of analysis. During the experimental test, the strain rate was changed from 10^{-3} /s to 10^{-2} /s at axial strain 0.065 (mm/mm) and then back to 10^{-3} /s at axial strain 0.11 (mm/mm). This jump in the strain rate is simulated using the proposed method. Figure 8 shows the comparison of simulated and experimental results. From this comparison, we can see that the applied technique reasonably predicted the experimental behaviour during the change in strain rate. There is little numerical noise in the results of simulation during the change of strain rate. Initially, the noise was large. To minimize it, a control was applied on the strain increment using the code of USDFLD. The maximum strain increment of less than 15% was found to reduce the noise to a reasonable value.

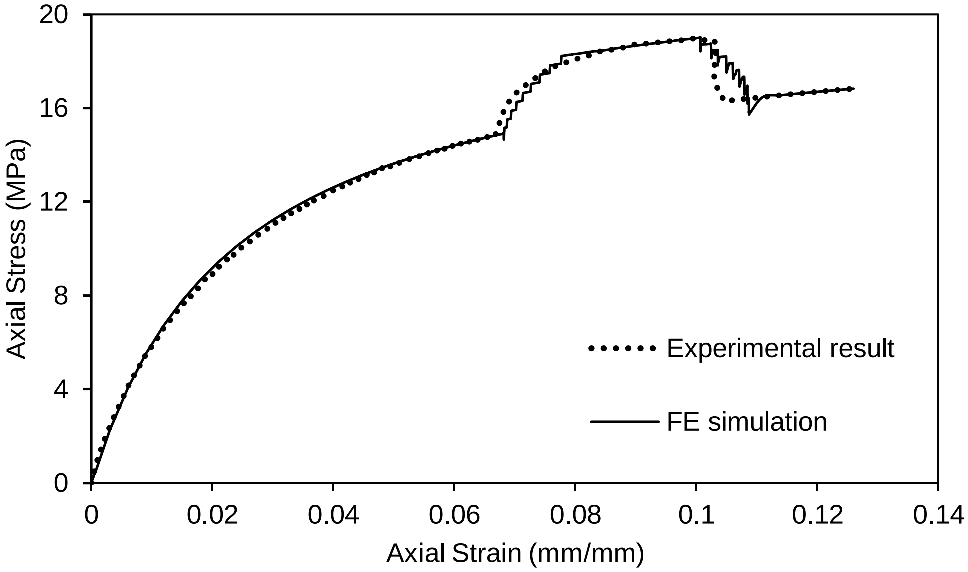

Figure 8: Simulation of a jump in the strain rate

The proposed method also reasonably predicted the loading-unloading-reloading response found from the experimental tests. During experimental investigation, a cyclic test was conducted with the same strain rate of 10^{-3} /s for loading-unloading-reloading. Figure 9 compares the results of FE simulation and experimental investigation. This figure shows that the observed behaviour of cyclic loading can be reasonably predicted by the proposed method.

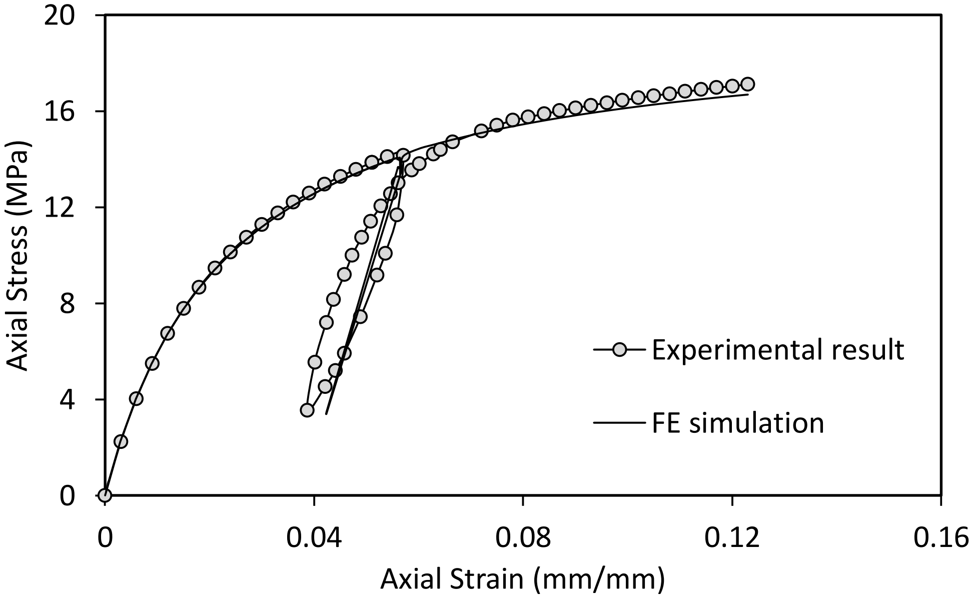

Figure 9: Simulation of cyclic loading test.

4 CONCLUSION

The time dependent nonlinear behavior of a MDPE material is systematically investigated using a series of uniaxial tension tests. The stress–strain responses are found to be highly nonlinear and strain rate dependent. During the experimental investigation, no strain rate history dependence was observed. A modelling technique is developed for simulating the behavior of MDPE pipe material using a commercially available FE software, Abaqus. It is found that, the modelling approach can successfully simulate the strain rate dependent stress–strain response observed in laboratory tests. It can also reasonably simulate the loading-unloading-reloading response and a jump in the strain rate.

5 ACKNOWLEDGEMENTS

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