EXPERIMENTAL TESTS AND NUMERICAL SIMULATION OF THE PLASTIC CYCLIC BEHAVIOUR OF SIMPLE STEEL COUPONS

G.C. Manos1, A. Nalmpantidou2, V. Kourtides3

1 Professor and ex-Director of the Lab. of Strength of Materials and Structures, Aristotle University
e-mail: gemanos@civil.auth.gr

2 Postgraduate student, Lab. of Strength of Materials and Structures, Aristotle University
e-mail: a.nalmpantidou@posteo.de

3 Dr. Civil Engineer, Research Ass., Lab. of Strength of Materials and Structures, Aristotle University

Keywords: Steel T-beam specimens, Simple steel coupons, Monotonic and Cyclic Load, Numerical Simulation, Comparison of measured and predicted response, Cyclic behaviour

Abstract. The cyclic response of steel beam-to-column connections under a cyclic sinusoidal loading history was studied. The experimental investigation included a number of full-scale specimens having a cross section of IPE240 or IPE300 and a height of 1.0m. This part of the specimen was rigidly connected to a much stiffer steel beam thus representing a steel beam-to-column connection under investigation. Instrumentation was provided to record both the applied moment as well as the deformation of the specimen in the region of the connection in terms of plastic hinge rotation. Simple steel coupons were taken from these T-beam specimens after testing having the shape of an orthogonal prism. The cross-section of these coupons was 6.2mm x 8.0mm and their height equal to 16.5mm. Each coupon was extended at either end to a much larger and thicker part enabling its attachment to the loading ring which consisted of a dynamic actuator capable to apply the desired cyclic load with a sinusoidal distribution having a given amplitude and frequency. A number of such simple steel coupons were tested and their response is presented and discussed having as main variable the nature of the load (monotonic or cyclic) and the variation of the loading frequency. From the observed behaviour it can be concluded that an increase in the strain rate results in an increase of the stress values beyond the yield. Next, a numerical study is performed in an effort to simulate the observed behaviour of these simple steel coupons. It can be concluded that the combined constitutive law can be quite successful in yielding realistic prediction of the cyclic response provided the appropriate values of the parameters defining this constitutive law are predetermined for the strain rate at hand. The numerical predictions employing the isotropic hardening constitutive law do not achieve the same degree of agreement with the observed behaviour, especially when the comparison is made on the cyclic response results. However, this type of numerical simulation is generically sensitive to the variation of the strain rate effect through the option of the dynamic increase factor (DIF).
1 INTRODUCTION

Steel frame structures are commonly used in seismic areas because of their excellence on seismic resistance. This type of structures are usually composed of moment resistant frames whereby the performance of beam-to-column connections are of particular importance especially when these structures are subjected to strong earthquake ground motions [1, 2, 5]. Usually these connections undergo large moment reversals during the earthquake excitation, thus it is important to exhibit stable plastic flexural response in order to provide dissipative capability, without the development of undesired damage patterns, and in this way prevent any kind of local or global instability. However, two recent earthquakes, in Northridge, California 1994 and Kobe Japan 1995, revealed the vulnerability of this type of construction. Premature cracks were observed at welded connections of steel beam-to-column joints leading to brittle failure without prior warning (obvious yielding) at the area around the weld. Such a failure mode or the development of local buckling, when beam-to-column connections undergo low-cycle fatigue seismic-type of loading, is of particular research interest [3, 4, 9 and 18].

The fatigue life of steel beam-to-column joints depends on the amplitude of the imposed loading cycles and the hysteretic behavior of the constituent material that is linked with the amplitude and rate of the developing plastic strains. In order to investigate the fatigue life of steel beam-to-column joints several fatigue testing investigations have been proposed leading to tests that can be categorized in two groups. Testing regimes in which the elastic strain amplitude is higher than the plastic strain amplitude and testing regimes in which the plastic strain dominates. The first type of tests is generally referred as high cycle fatigue (HCF); these tests typically involve more than $10^6$ cycles to cause failure. The second type of tests is named low cycle fatigue (LCF) test and the number of cycles to failure generally ranges from $10^2$ to $10^4$ cycles and this is usually employed for testing the seismic performance of steel beam-to-column joints [6, 7, 8, 12, 13, 19].

In a previous investigation by Manos, Nalmpantidou and Anastasiadis ([16]) the performance of steel beam-to-column joints was studied first by examining steel beam-to-column welded joint specimens at the laboratory subjecting them to cyclic seismic-type low-cycle fatigue loading and then by numerically simulating the observed performance of the same specimens. Similar studies have been performed in the past by other researchers. Despite the fact that many similar experiments have been performed in the past [6, 8], this investigation provided at first hand all the information required for the numerical analyses. That is, the exact geometric and material characteristics of the specimens as well as specific information on the type of loading conditions and on the measured response. The numerical simulation was performed utilizing a commercial software package that is thought to be suitable to simulate the observed response and the non-linearity that developed and included large plastic strains and local instabilities.

One parameter that was found to be of significance in this investigation was the definition of the material characteristic of the steel T-beam specimens that were investigated ([10], [14], [16] and [18]). The T-beam specimens were tested under cyclic load with the frequency of this loading being one of the variables that was studied. For this reason it was necessary to study the material properties in light of the fact that the imposed cyclic loading was not of the constant slow-rate monotonic type that usually characterizes the material properties of steel structural elements. For this purpose the following experimental sequence was carried out. From each of the tested steel T-beams a number of coupon samples were taken, as is described in section 2. These samples were tested in axial tension/compression under cyclic loading with the frequency of the loading being one of the main variables. In addition, apart from these samples being tested by cyclic load additional samples of the same T-beam speci-
mens were tested applying the tension in a monotonic way. From all these tests results were obtained that shed some light on the influence of the nature of loading (cyclic or monotonic) as well as on the frequency of this loading. Summary results of this experimental sequence are presented and discussed in section 3. The numerical analysis of the observed performance is presented in section 4. The ABAQUS commercial software package was utilized for this purpose.

2 MATERIALS AND EXPERIMENTAL SETUP

The coupon samples for the tests aiming for the material characterization were taken by removing parts of the flanges of the previously tested T-beam specimens. The testing of these T-beam specimens is described in the work by Manos et al. (2015 [16]) and is not repeated here. These removed flange parts were from sections of the T-beam specimens that were away from the plastic hinge locations, which developed during the T-beam tests ([16]). These T-beam specimens after the removal of the flange parts for forming the coupons for axial cyclic/monotonic tests are depicted in figures 1a and 1b.

The coupons to be tested were formed by machining the parts removed from the flanges, as shown in figures 2a and 2b. These coupons had a narrow central part of relatively small cross section. This narrow central part was of small length ($\ell = 16$mm) and it was this part that
was designed to provide the necessary information for the material characterization. This narrow central part was extended to two wide parts. Through these two larger parts the coupon was attached to the loading reaction frame. These top and bottom wide parts were provided with holes in order their attachment to the loading reaction frame to approximate pinned support conditions (see figures 2a, 2b, 3a and 3b). In figure 3b part of the reaction frame is also shown. At the top and bottom of the coupon in figures 3a and 3b steel brackets are employed to attach the coupon sample using cylindrical pins. These brackets are in turn firmly attached to the reaction loading frame. At the top bracket a load cell is also attached that monitors the variation of the applied axial load.

The cross section of the narrow part remained constant all along its 16mm length. Its dimensions (x, y) were accurately measured (figures 4b and 4c). Moreover, strain gauges were attached at the middle of all the sides of this rectangular prismatic narrow part. These strain
gauges were placed in the longitudinal direction of this steel prismatic part in order to measure the variation of the axial strain that developed during the variation of the axial load. The dimensions of the cross section of this narrow part combined with its length dictated almost uniform tension / compression conditions prohibiting the development of any distortions from local buckling, especially when large plastic strains developed in this narrow central part. Through the readings of the strain gauges the eccentricity of the axial load application could be checked and controlled.

3 OBSERVED PERFORMANCE AND CORRESPONDING MEASUREMENTS.

As already mentioned, one of the main variables of this investigation was the nature of loading, being either cyclic or monotonic. The second variable was the frequency of the cyclic loading or the rate that the monotonic loading was applied, as will be indicated in what follows.

3.1 Monotonic loading

In what follows a summary of results are presented obtained when the tested specimens were subjected to monotonic axial tensile load. When these results are presented the code name of the T-beam of their origin is indicated together with the characterization of the applied load in terms of loading rate (slow or fast). In figure 5a the axial stress versus axial strain response is shown from two coupons taken from T-Beam 9R1; one of them was tested with slow strain rate whereas the other one with fast strain rate. As can be seen from this figure, this variation of the strain rate during the monotonic application of the applied load resulted in a significant change in the yield stress value as well as in the plasticized part of the response beyond the yield point. In figure 5b the axial stress versus axial strain response is shown from two coupons both of them tested with slow strain rate; one of them was taken from T-Beam 9R1 whereas the other one from T-beam 10R1. As can be seen from this figure the obtained response from these two coupons is rather similar. In general, the increase of the strain rate from slow to fast results in an increase in the yield stress as well as in the stress values beyond the yield point.

![Figure 5a. Coupons taken from T-Beam 9R1 tested with slow and fast strain rate](image1)

![Figure 5b. Coupons taken from T-Beam 9R1 and T-beam 10R1 both tested with slow strain rate](image2)

3.2 Cyclic loading

In figure 6 the obtained axial stress versus axial strain response is shown as it was measured from a coupon taken from T-beam 8R1 specimen and subjected to a number of cyclic loading
The strain rate during all these tests was rather fast as it resulted from the application of the axial tensile / compressive load from a sinusoidal variation having a frequency of 2.0Hz.

Figure 6a. Cyclic response with axial load varying in a sinusoidal way with a frequency of 2.0Hz. Coupon taken from T-Beam 8R1 tested with a rather fast strain rate.

Figure 6b. Cyclic response with axial load varying in a sinusoidal way with a frequency of 0.1Hz. Coupon taken from T-Beam 9R1 tested with a moderately fast strain rate.

Figure 7. Cyclic response when axial load is varying in a sinusoidal way with frequency values in the range from 0.01Hz to 1.0Hz. Coupons taken from T-Beam 6R1 tested with slow as well as with fast strain rate.

In figure 6a the cyclic response of a coupon taken from T-Beam 8R1 is shown. This response resulted by applying the axial load in a sinusoidal way with a frequency of 2.0Hz thus producing a rather fast strain rate. In figure 6b the cyclic response of a coupon taken from T-Beam 9R1 is shown. This response resulted by applying the axial load in a sinusoidal way with a frequency of 0.1Hz thus producing a moderately fast strain rate. In figure 7 the cyclic response of a coupon taken from T-Beam 6R1 is shown. This response resulted by applying the axial load in a sinusoidal way with a frequency that is varying in the range from 0.01Hz till 1.0Hz. The response obtained during the test whereby the cyclic load was varied with a frequency equal to 0.01Hz is considered as a rather slow strain rate test whereas the one with a frequency equal to 0.1Hz as a rather moderately fast strain rate test. Finally, the response obtained during the test whereby the cyclic load was varied with a frequency equal to 1.0Hz is considered as a rather fast strain rate test. As can be seen from these figures (6a, 6b, and 7) the yield point can be hardly distinguished from the obtained axial stress versus axial strain response. However, as can be seen in figure 7, the variation of the strain rate during the cyclic application of the applied load resulted in a significant change in the plasticized part of the
response beyond yield as it was also observed in figure 5a for the monotonic application of the load. It can be concluded from both figures 5a and 7 that the increase in the strain rate results in a noticeable increase both at the yield stress as well as at the stress values beyond the yield point for strain values larger that the yield strain.

In figure 8 the axial stress versus axial strain response is shown from four coupons; three of them are taken from T-Beam 9R1 and one of them is taken from T-beam 10R1. Coupon 9R1 was tested with a cyclic loading frequency equal to 2.0Hz (Tests 1, 4, 5) producing a rather fast strain rate. Two coupons from the same T-beam 9R1 were tested by applying the tensile load in a monotonic way; one of them with a slow strain rate (INSTRON static 9R1-5) and the other one with a fast strain rate (INSTRON quick 9R1-5). Finally, the fourth specimen was taken from T-beam 10R1 and was tested by applying monotonic load with a slow strain rate (INSTRON static 10R1-3). The two main observations that were made before can also be seen in this figure.

a) An increase in the strain rate during the monotonic application of the load resulted in an increase in the yield stress value as well as in the stress values of the plasticized part of the response beyond the yield point.

b) The observed axial stress versus axial strain response from different coupons subjected to the same slow strain rate monotonic load is quite similar.

c) The application of the cyclic load with slow, moderately fast or rather fast strain rate resulted in axial stress versus axial strain response whereby the yield point is hardly distinguishable. Thus the strain rate effect can be clearly seen.

d) The application of the cyclic load with slow, moderately fast or rather fast strain rate resulted in axial stress versus axial strain response that has stress values beyond the yield point that exhibit a noticeable increase with the increase in the strain rate.

e) From the limited results presented here the effect of the cyclic nature of the loading results in a more pronounced increase of the stress values with the increase in the strain rate than when the load is applied in a monotonic way.
4 NUMERICAL SIMULATION OF THE TENSION AND CYCLIC TESTS

4.1 Numerical modeling.

As mentioned in section 2 simple specimens having the shape of an orthogonal prism were taken from the flanges and were applied to monotonic tension or to cyclic tensile/compressive load with a sinusoidal time variation having a given amplitude and frequency. A number of such simple specimens were tested and their results are presented and discussed in section 3 having as main variable the variation of the loading frequency and the nature of the loading (monotonic or cyclic). In order to simulate numerically the behavior of these specimens a numerical study was performed utilizing the commercial software package ABAQUS [11].

The orthogonal prism of the experimental sequence (figure 9a), which was represented through the finite element 2-D mesh, is shown in figures 9b. The prism was considered to be represented with absolute fixity conditions in the numerical simulation on the top side whereas on the bottom side either the monotonic or the cyclic load was applied. The other two sides were left unconstrained. However, the rigid body in-plane as well as the out-of-plane horizontal displacement response was also constrained.

In order to simulate the variation of the load in time as either fast or slow monotonic load or as cyclic load with varying sinusoidal cyclic frequency, the displacement control option was utilized whereby an imposed displacement was defined as a function of time and displacement amplitude, as shown in figures 10a to 10d. Dynamic implicit analyses were in order for this software to take into account the different load frequencies. Following the load variation that was applied during testing the numerical analyses were also performed with monotonic load (with either slow or fast strain rate) and with cyclic load (again with either slow, moderate or fast strain rate, figures 10a to 10d). The imposed displacement variation was introduced to the software in tabular form to identical with the one that was applied to the corresponding specimen during the experimental sequence. The adopted discretization
scheme (figure 9b) is believed to be considerably fine in an effort to capture numerically the observed behavior.

Figure 10. Time variation of the imposed displacement either monotonic or cyclic during the various numerical analyses

4.2 Material modeling

In the framework of the numerical investigation a parametric study was conducted that focused on the way the steel material properties were introduced in the numerical simulation. Two different approaches were tried. According to the first approach the measured tensile steel properties were modified accordingly in order to be introduced in the numerical simulation through the ABAQUS combined hardening material constitutive law whereas in the second approach the measured properties were introduced in the numerical simulation through the ABAQUS isotropic hardening constitutive law together with an option to account for different strain rates. There are several ways in this commercial software package [11] to define a combined hardening material constitutive law in order to capture the cyclic response of a specimen. In this study the combined hardening constitutive law is defined through the values that are given to certain relevant parameters. These parameters are a) \( \sigma_0 \), the yield stress at zero equivalent plastic strain, b) \( C_l \) and \( \gamma \) (material constants). Values for these parameters were taken from the work of Nip et al. [17]. Nip at al. followed a certain experimental process whereby these parameters were defined in an explicit way through measurements obtained from tests of steel samples, similar to the ones presented in sections 2 and 3. The values that were found by Nip et al. [17] were utilized in the parametric study that was performed in the present work.
The second material constitutive material law that was employed through this commercial software [11] is denoted as isotropic hardening together with an option to account for different strain rates. The isotropic hardening constitutive law was defined by true stress-true strain data from the monotonic axial tension test of specimen 9R1-5 with slow strain rate (figure 8). In order to define the strain rate effect the use of a dynamic increase factor (DIF) was utilized based on the work of Malvar and Crawford [15]. Values for DIF were calculated and introduced as input in tabular form in terms of a ratio of the yield stress versus the equivalent plastic strain rate to be used in the particular case being analyzed. The work of Malvar and Crawford [15] is based on numerous experimental data from a literature review on the effects of strain rates on the properties of steel reinforcing bars for reinforced concrete structural elements. The dynamic increase factor (DIF) is the amplification by DIF of the value a certain mechanical property (yield stress or maximum stress) has under low strain rate loading conditions (static) to another condition whereby because of the nature of loading (dynamic) the strain rate has a larger value than before. A relationship is proposed by Malvar and Crawford ([15]) that a DIF value can be derived for a given strain rate increase and thus evaluate through this DIF the corresponding for this increased strain rate amplified yield and ultimate stress values. This formulation is valid for bars with yield stresses between 290 and 710 MPa and for strain rates between $10^{-4}$ sec$^{-1}$ and 225 sec$^{-1}$. Figure 11 depicts the variation of DIF with the variation of the strain rate. This approach was presently followed use as reference control properties the yield stress found for the slow rate monotonic axial tension test with coupon 9R1-5 (see figure 8).

![Figure 11. Dynamic increase factor which have been considered for the numerical investigation](image1)

![Figure 12. Numerical simulation of a monotonic load test with the combined hardening constitutive law. It is applied for coupons 9R1-5 undergoing either slow strain rate or fast strain rate loading.](image2)
4.3 Numerical results for monotonic axial tensile load cases

Figure 12 shows the axial stress – axial strain monotonic tensile response obtained from the numerical analysis of coupon 9R1-5 loaded under slow strain rate conditions and coupon 9R-5 loaded under fast strain rate conditions. The constitutive law in both analyses is that of the combined hardening. It can be easily seen that, through this type of constitutive law, the obtained response is insensitive to the change of the strain rate, despite the fact that this was introduced through the input imposed displacement variation in time whereby in the first case the loading sequence lasted 200 seconds whereas in the later case the same loading sequence only 2.5 seconds, as is indicated in figure 12. The obtained response for both cases is almost identical apart from the fact that the numerical simulation for the fast strain rate condition results in certain numerical instabilities, as is pointed out in figure 12.

Figure 13a. Numerical axial stress-strain response with isotropic hardening and DIF for coupons 9R1-5 subjected to either slow or fast strain rate monotonic load.

Figure 13b. Numerical axial stress-strain response with isotropic hardening and DIF for coupons 9R1-5 and 10R1-3 subjected to either slow or fast strain rate monotonic load.

Figure 13a depicts the axial stress-strain numerical response employing isotropic hardening constitutive low together with the DIF options for coupons 9R1-5 submitted to monotonic tension load with either slow (duration of loading 700 seconds) or fast strain rate (duration of loading 2.5 seconds). As can be seen, the numerical simulation is quite sensitive to the effect of the strain rate variation. Moreover, the numerical response agrees quite well with the observed response for strain values smaller than 6000 micro-strains. The same comparison is included in figure 13b this time for strain values up to 40000 micro-strains. In figure 13b the observed behaviour of coupon 10R1-3 is also included. Again it can be seen that the numerical simulation including the isotropic hardening with the DIF option is sensitive to the strain rate variation. In the case of the slow strain rate there is a certain discrepancy between predicted and observed stress values for strains larger than 10000 micro-strains and smaller than 20000 micro-strains. Similarly, in the case of the fast strain rate there is again a certain discrepancy between predicted and observed stress values for strains larger than 6000 micro-strains and smaller than 25000 micro-strains.

In figure 14a depicts the axial stress-strain numerical response employing combined hardening constitutive low for coupons 9R1-5 submitted to monotonic tension load with slow strain rate conditions (duration of loading 700 seconds). From trial and error reasonably good agreement between numerical predictions and measured response was achieved for yield stress equal to 320 MPa and material parameters $C1=4300$ and $\gamma P=40$, as indicated in this figure. In Similarly, figure 14a depicts the axial stress-strain numerical response employing combined hardening constitutive low for coupons 9R1-5 submitted to monotonic tension load with fast strain rate conditions (duration of loading 700 seconds). From trial and error, reasonably
good agreement between numerical predictions and measured response was achieved for yield stress equal to 370MPa and material parameters $C_1=6000$ and $\gamma_1=40$, as indicated in this figure. From the above numerical study it can be concluded that if such material characteristics defining the combined constitutive law were available for a given strain rate condition (as is the case here) then it is reasonable to expect that the same numerical simulation employing this material constitutive law could also be successful in simulating the behaviour of more complex structural elements under loading introducing similar strain rate conditions.

4.4 Numerical results for cyclic axial tension / compression load cases

In this section the same approach that was tried in section 4.3 for the monotonic load cases is applied here for the cyclic load cases. Figure 15 depicts the axial stress-strain numerical response employing isotropic hardening constitutive low together with the DIF options for coupons 9R1-5 submitted to cyclic tension / compression load resulting in a fast strain rate condition (variation in time of the sinusoidal cyclic load equal to 2.0Hz). As can be seen in this figure, the numerical predictions overestimate both the observed yield and strength values. Moreover, the predicted hysteretic loops are rather of a square than of an elliptical shape that is exhibited by the measured hysteretic response.

Figure 15. Axial stress-strain numerical response employing isotropic hardening constitutive low together with the DIF options for coupons 9R1-5 submitted to cyclic tension / compression load resulting in a fast strain rate condition
Figure 16 depicts the axial stress-strain numerical response employing combined hardening constitutive low for coupons 9R1-5 submitted to cyclic tension / compression load resulting in a fast strain rate condition (variation in time of the sinusoidal cyclic load equal to 2.0Hz). From trial and error, reasonably good agreement between numerical predictions and measured response was achieved for yield stress value equal to 370MPa and material parameters $C1=6000$ and $\gamma l=40$, as indicated in this figure. The values of these parameters are the same as the ones employed in the numerical simulation of the monotonic case of figure 14b. It should be noted that the parameter $C1$ was assigned a value $C1=4300$ in the monotonic load with slow strain rate case (figure 14a). The agreement between predicted and measured cyclic response achieved by the numerical analysis employing yield stress value equal to 370MPa and material parameters $C1=6000$ and $\gamma l=40$, is quite good, as can be seen in figure 16. This good agreement applies both to the measured and predicted yield and ultimate stress values as well as to the shape of the hysteretic loops (figure 16).

![Figure 16. Axial stress-strain numerical response employing combined hardening constitutive low for coupons 9R1-5 submitted to cyclic tension / compression load resulting in a fast strain rate condition](image)

From the above numerical study it can again be concluded that the combined constitutive law is quite successful in yielding realistic prediction of the cyclic response; however, in order to be sensitive to the strain rate effect the appropriate values of the parameters defining this constitutive law (such as $\sigma_0$, the yield stress at zero equivalent plastic strain, and $C1$ and $\gamma$ the material constants) must be somehow be predetermined for the strain rate at hand. In this case, the numerical simulation employing the same material constitutive law is reasonable to believe that it would also be successful in simulating the behaviour of more complex structural elements for loading introducing similar strain rate conditions.

On the contrary, the numerical predictions employing the isotropic hardening constitutive law do not achieve the same degree of agreement with the observed behaviour, especially when the comparison is made on the cyclic response results. However, this type of numerical simulation including the isotropic hardening constitutive law is sensitive to the variation of the strain rate effect through the option of the dynamic increase factor (DIF). Thus, in this case this predetermining of the appropriate values of the material parameters is not necessary.

5 CONCLUSIONS

- An extensive experimental sequence was conducted testing relatively small dimension coupons to axial monotonic or cyclic loading with a variety of strain rate conditions. These coupons were formed from steel parts taken from the flanges of T-beam steel
section that were previously tested to destruction by cyclic seismic-type loading. The current study is an extension of the previous research in an effort to first quantify the strain rate effect in a controlled way and next to be able to effectively simulated utilizing existing numerical tools. From the current investigation the following findings could be stated.

- An increase in the strain rate during the monotonic application of the load resulted in an increase in the yield stress value as well as in the stress values of the plasticized part of the response beyond the yield point.

- The application of the cyclic load with slow, moderately fast or rather fast strain rate resulted in axial stress versus axial strain response whereby the yield point is hardly distinguishable. Thus the strain rate effect can be clearly seen.

- The application of the cyclic load with slow, moderately fast or rather fast strain rate resulted in axial stress versus axial strain response that has stress values beyond the yield point that exhibit a noticeable increase with the increase in the strain rate.

- From the subsequent numerical study it can be concluded that the combined constitutive law is quite successful in yielding realistic prediction of the cyclic response; however, in order to be sensitive to the strain rate effect the appropriate values of the parameters defining this constitutive law (such as $\sigma_0$, the yield stress at zero equivalent plastic strain, and $C_I$ and $\gamma$ the material constants) must be somehow be predetermined for the strain rate at hand. In this case, the numerical simulation employing the same material constitutive law is reasonable to believe that it would also be successful in simulating the behaviour of more complex structural elements for loading introducing similar strain rate conditions.

- On the contrary, the numerical predictions employing the isotropic hardening constitutive law do not achieve the same degree of agreement with the observed behaviour, especially when the comparison is made on the cyclic response results. However, this type of numerical simulation including the isotropic hardening constitutive law is sensitive to the variation of the strain rate effect through the option of the dynamic increase factor (DIF). Thus, in this case this predetermining of the appropriate values of the material parameters is not necessary.

- Both the experimental and the numerical part of this study are still under way; thus the above conclusions should be considered as preliminary.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of M. Theofanous, Dr. Civil Engineer, Lecturer at the Department of Civil Engineering of the University of Birmingham, for all his valuable advice related to the numerical simulation. The technical assistance of T. Koukouftopoulos in preparing the experimental arrangement is also gratefully acknowledged.

- To the memory of Ray W. Clough, Professor Emeritus of the University of California, at Berkeley, U.S.A.

REFERENCES


