Congo Sciences

Journal en ligne de l'ACASTI et du CEDESURK
ACASTI and CEDESURK Online Journal
ISSN: 2410-4299, an International Journal

Influence of Low Strain Rate on Uniaxial Tensile Test Parameters of Reinforcing Steel Bars.

Michel KIMUHA KIRUMBA* and Richard VALL RICARDO

Paper History
Received:
July 09, 2019
Revised:
October 13, 2019
Accepted:
November 01, 2019
Published:
November 27, 2019

Keywords:
Yield, Ultimate, Tensile, Section Reduction, Strength, Elongation, and Congo.

ABSTRACT

This study investigates experimentally the uniaxial stress-strain behavior of reinforcing steel bars under various low strain rates, quasi-static from 0.001 12 s^{-1} to 0.006 70 s^{-1}. The main objective of these tests was to give an indication of the effect of the low strain rate variation on the uniaxial, monotonic, stress-strain, elongation-strain, section reduction-strain curves of reinforcing steel bars. The results of the tensile tests indicate that the yield strength and the ultimate tensile strength of reinforcing steel bars increase as the strain rate increases; while the elongation and section reduction of reinforcing steel bars do not appear to be substantially affected by the low strain rate variation. It was also observed that the smaller reinforcing steel bars were more affected by low strain rate variation, although sometimes inconsistently, than the relatively bigger ones. Thus, one should be more precautious while testing smaller reinforcing steel bars. Furthermore, a new regression formula is proposed for both yield strength and ultimate tensile strength with an "R squared" of 80%. This formula may be used as a means by which some quick verifications and checking may be done.

Département de Génie Civil, Faculté Polytechnique, Université de Kinshasa, Kinshasa/ Lemba, République Démocratique du Congo.

* To whom correspondence should be addressed: *kirumbamichel@yahoo.fr*

INTRODUCTION

Materials used in sectors such as transportation (highway, road, tunnel, etc.), building industry, hydraulic construction (dam, dike, etc.), are stressed in different ways with much variation of solicitations from one another. Such variations may impact the behavior and response of those structures. Strain rate or load rate is one of the key parameters that feed such variations. And, for decades many researchers have studied the effects of strain rate on the mechanical properties of various materials especially concrete and metals [e.g. MONJOINE, 1944; RESTREPO-POSADA et *al.*, 1994; FILIATRAULT and HOLLERAN, 2001; ZHANG et *al.*, 2018].

It is commonly recognized that for metals and alloys the plastic flow behaviors and the corresponding deformation mechanisms are vastly influenced by the loading rate [WEI et al., 2004 ; WEI, 2007; GEIGER et al., 2008 ; MISHRA et al., 2008; BOYCE and DILMORE, 2009 ; CADONI et al., 2009 ; XIONG et al., 2009 ; YU et al., 2009; SUO et al., 2013; YUAN et al., 2016]. In addition, the strain rate is established to be one of the factors affecting the resistance to plastic deformation [WEI, 2007; MISHRA et al., 2008; SUO et al., 2013].

A tremendous amount of work has been done to determine the impact of stain rate on engineering characteristics of steels. Necessarily, only a few studies will be mentioned herein. Among those researchers Ludwik was considered by DAVIS [1938] to be perhaps the first researcher who in 1909 observed the effects of varying strain rate on the mechanical properties of metals. Many others have also pointed out in convergence view the effect of strain rate on metals engineering parameters. For instance, it was observed that the strain rate had negligible effect on the elastic modulus and the stiffness of steel in the strain-hardening range [WAKABAYASHI et al., 1984]. It was also recognized that, as the strain rate increases, the yield strength and tensile ultimate strength of steel increase linearly with logarithmically increasing strain rate [SOROUSHIAN and CHOI, 1987; FUJIMOTO et al., 1988; KASSAR and YU, 1992; OBATA et al., 1996; GIONCU, 2000; SANCHEZ and PLUMIER, 2000], while ratio between the ultimate stress and the yield stress drops, and higher strength steel is less susceptible to strain rate effects compared to lower strength steel [MONJOINE, 1944; RESTREPO-POSADA et al., 1994].

The same conclusions were made by PENIN [2010] and DUNAND [2013]. PENIN observed an increase of stresses on a steel DP450 with the increase of strain rate but this time in uniaxial and biaxial tensile tests with strain rate from 10^{-3} s^{-1} to 10^{3} s^{-1}. Likewise, DUNAND presented similar conclusions after conducting monotonic tensile test on TRIP780 steel.

Although monotonic tensile test was the most common type of steel test used for these studies, most of these researches were conducted with more focus on the influence of intermediate to high strain rate on concrete and metals in order to evaluate the response of structure design for dynamic solicitations such as seismic ones during an earthquake. Very limited researches have been carried out on the effects of strain rate on reinforcing steel under monotonic tensile test at low strain rate such as those recommended by ISO 6892-1 [2016] at ambient temperature.

In fact, ISO 6892-1 recommended a couple of ranges of strain rate to be used for the determination of the tensile strength, percentage elongation fracture, percentage total extension at maximum force, percentage plastic extension at maximum force, and percentage reduction area; especially after determination of the required yield/proof strength properties, the estimated strain over the parallel length. Among them the extreme ranges are 0.000 25 s^{-1} and 0.006 70 s^{-1}, both of them with a relative tolerance of ± 20%.

Accordingly, in common practice these ranges are used with no further correction. Based on assumption that no significant variation should be found between results from the preceded ranges. Unless, this seems to not be the case. Indeed, the EU funded project TENSTAND [LOVEDAY et al., 2004] which addressed i) the issues of computer controlled tensile testing, ii) validation of tensile software, iii) the issues of speed of testing and iv) the measurement of Modulus with a view to providing a sound technical basis for further development of the Standard, expressed the fact that while most tensile testing Standards specify the rate at which the testing should be carried out, still there is a variation from results made either form tests carried slowly or rapidly, or from tests conducted under relatively stable strain rate. They asserted also the fact that the tensile strength, formerly known as the ultimate tensile strength was less sensitive to testing speed, and thus the testing rate was permitted to be increased after the determination of proof strength, or when upper and lower yield strengths, had been determined. This enabled a shorter time of testing.

Unlikely, no much attention seems to be caught from researchers in order to light these asserts. Therefore, it is observed that the strain rate influence steel parameters value only from low strain rate to high one. This concern is expressed as no much attention have been paid to a small range such as 10^{-5} s^{-1} to 10^{-4} s^{-1}.

KIRUMBA and RICARDO [2019] pointed out the major role of engineering properties of steel bars in design and construction processes, especially in Kinshasa Industry. They expressed also the importance of those parameters to be determined accurately and known by users before being applied for design or construction purposes. Consequently, clarification of the role of low strain rate on the steel bars properties should be of paramount importance.

In order to comprehend the influence within relatively small range between low strain rate on engineering parameters of reinforcing steel bars, an investigation has been conducted over a number of reinforcing steel bars with five different diameters in size. As stated by FROLI and ROYER-CARFAGNI [1999], the simplest and by far most widely used test for this purpose is the tensile test, hence monotonic tensile test was conducted for investigating the effect of low stain rate on engineering properties of steel bars. Alike of 300 specimens were tested in the Strength Materials Laboratory of Civil Engineering department, Polytechnic Faculty, of the University of Kinshasa.

MATERIALS AND METHOD

Equipment and Specimens used

The test program was conducted in a 200-kN-capacity, automatic operated, servo-hydraulic (MATEST S.P.A. universal testing machine). The two ends of the steel coupons were gripped into the crossheads of the loading frame. The applied load was measured automatically by the testing machine displayed onto computer screen. The average tensile strain of the steel was obtained from the ISO 6892-1-Method A2, which is based on the crosshead separation rate. The ISO 6892-1-Method A2 is used in indirect manner in order to estimate the estimated strain rate over the parallel length. For each test, the tensile stress-strain curve of the steel was recorded by a data acquisition system.

Monotonic tensile tests were conducted on three hundred (300) cylindrical reinforcing steel coupons for different strain rates within a small range. The range of strain rate considered was typical low stain rate recommended by ISO 6892-1 [2016] at ambient temperature under quasi-static condition (0.00112/s, 0.00223/s, 0.00447/s, and 0.00670/s).

The detailed description of the sample preparation and the operating procedures for monotonic tensile test obtaining steel bars engineering properties can also be found in our previous paper [KIRUMBA and RICARDO, 2019]. Tensile tests at four (4) different strain rates (0.00112/s, 0.00223/s, 0.00447/s, and 0.00670/s) were conducted in the present study. For every company, fifteen (15) experiments were conducted for each strain rate to check the repeatability. The quasi-static uniaxial tensile tests were conducted using a universal testing machine aforementioned.

Products from four (4) local companies were used. These local companies are the same as those revealed by writers' previous paper [KIRUMBA and RICARDO, 2019]. The samples were collected from four (4) different companies as earlier stated. Thus, there were twenty (20) samples from four (4) different companies which were considered for the tensile tests.

In clear, the writers disposed:

15 Samples of 6-mm diameter	:	For every company
15 Samples of 8-mm diameter	:	For every company
15 Samples of 10-mm diameter	:	For every company
15 Samples of 12-mm diameter	:	For every company
15 Samples of 14-mm diameter	:	For every company

All of them were ribbed surface steel bars.

Samples Preparation

Initial overall geometric dimensions were measured on all specimens prior to testing. An alphabetical order such as A, B, C and D, was used in order to labeled all the specimens selected for the study. This order of identification is neither increasingly nor decreasingly in respect to the corresponding specimen properties. In addition, this order has been used randomly only for the current experimental identification purpose. Every letter implies a single company. In each diameter for a company, fifteen (15) specimens were tested for complete test. The value presented in this paper is an average of fifteen (15) for each test.

The lengths 400-mm were used for all diameter bars from 6 to 14 mm. Each specimen diameter is measured in at least three places and the average is calculated and recorded as the diameter value.

Method of testing

Tensile test is a destructive one, performed at ambient temperature, consists of imposing an increasing deformation at a constant speed and measuring the force required to impose this deformation. An extensometer measures the elongation of the specimen, and a dynamometer measures the effort. The result is displayed on a screen or plotter via a data acquisition system [BS EN 10002-1, 2001].

The current study used a quasi-static tensile uniaxial test which is performed under relatively slow speeds. In such regime inertial effects are not considered in equilibrium equations and analysis. In addition, unlike in intermediate and high speeds tests, the effects of heat are not considered as the heat has time to dissipate so that one can consider the test as isotherm.

A test was kept on until the specimen fractured and there was a sudden drop in the load. Only results in which failures occurred in the free-length of the specimen were considered valid for the determination of the tensile strength.

RESULTS AND DISCUSSION

As there is no local standard currently available for tensile test, ISO 6892-1 [2016] is used in this study. The characteristics such as yield strength, ultimate tensile strength, elongation, and section reduction are calculated from information recorded in the tensile tests, and they are compared to one other while taking into account the strain rate variation.

The tensile strength was computed according to the following formula (1):

$$\sigma_t = \frac{P}{A_0} \qquad (1)$$

Where:

σ_t : Tensile stress,

P : Applied load,

A_0: Initial cross-sectional area of the sample.

Figure 1 depicts an example of data recorded in tensile tests. The graphs recorded from the three hundred (300) specimen tests were estimated to be too much to be contained in this paper. As such, only this one is shown here for illustration purposes. It should be warned that this does not mean all graphs have the same shape.

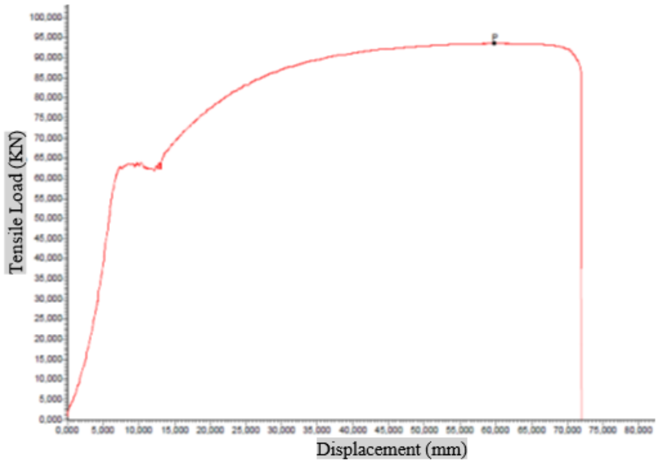


Figure 1 : Example of Data Recorded in Tensile Tests: Tensile load (KN) versus Displacement (mm)

The raw load-displacement data were stored on disk and later converted to engineering units. Figure 1 shows examples of the data recorded during a typical tensile test. Those data were used to compute yield strength, ultimate strength, elongation, and so on.

The strain was calculated using the formula (2) below:

$$\varepsilon = \frac{\Delta L}{L_0} \qquad (2)$$

Where:

- ✓ ε : Strain,
- ✓ ΔL : Elongation,
- ✓ L_0 : Original gauge length.

Yield strength was calculated from data taken from the graph (Load versus elongation). And elongation at fracture (or ductility) in percent (%), D, was computed from formula (3) as:

$$D = \varepsilon * 100 \qquad (3)$$

Hence, the mentioned elongation in the following pages refer to ductility in %.

Crossheads separation rate is defined by ISO 6892-1 as "displacement of the crossheads per time". Method A2 from ISO 6892-1 was used which is based on the crossheads separation rate. This method is used in indirect manner in order to estimate the estimated strain rate over the parallel length by applying formula (4).

$$V_c = L_c * \dot{e}_{L_c} \qquad (4)$$

Where:

- ✓ V_c : constant crosshead separation rate,
- ✓ L_c : parallel length,
- ✓ $\dot{e}_{L_c}$: estimated strain rate over the parallel length.

According to ISO 6892-1 percentage reduction of area, Z, can be calculated from formula (5):

$$Z = \frac{S_0 - S_u}{S_0} * 100 \qquad (5)$$

Where:

- ✓ S_0 : Original cross-sectional area of the parallel length,
- ✓ S_u : Minimum cross-sectional area after fracture.

From ISO 6892-1 the standard uncertainty, u, of the value of a parameter can be estimated from formula (6):

$$u = \frac{s}{\sqrt{n}} \qquad (6)$$

Where:

- ✓ s : standard deviation of the measurements,
- ✓ n : number of observations being averaged to report the result of the measurement under normal circumstances.

The above formulae were used for calculations throughout the current study. The results are presented in the follow section.

For every of the four (4) parameters of steel bars studied graphs were plotted. First, a set of two graphs are presented. Secondly, six graphs are added in Appendix section with more details. In the first set, two principal graphs are represented. Variations of the concerned parameters (yield strength, ultimate tensile strength, elongation, section reduction) of reinforcing steel bars with strain rate, and variations of the standard uncertainty (herein called uncertainty) of reinforcing steel with their diameter, are presented.

The first figures (Figures 2, 4, 6, and 8) of the two principal graphs expressed the variation of the concerned parameters (yield strength, ultimate tensile strength, elongation, section reduction), which are made from average values of the four companies (A, B, C, and D) based on their corresponding parameter.

The second figures (Figures 3, 5, 7, and 9) of the two principal graphs assert the variation of uncertainty of every parameter, which are based on the standard deviation performed from different strain rates and the number of observations being averaged to report the results of the measurements under normal circumstances (number of tests conducted and validated).

Another set of graphs is depicted in the Appendices A, B, C, and D. Those graphs show the variation of uncertainty of every parameter (yield strength, ultimate tensile strength, elongation, section reduction) respect to reinforcing steel bar diameters. The last one is made from average values from different strain rates. In addition, variation of the aforementioned parameter with strain rate for every reinforcing steel bar diameter (Ø6 mm, Ø8 mm, Ø10 mm, Ø12 mm, Ø14 mm) are plotted. The specificity of the second set of graphs (Appendices) is that variation of every single company for all reinforcing steel bars is expressed with the strain rate.

Yield Strength

The yield strength-strain curves for the reinforcing steel bars at various strain rates, and the uncertainty-reinforcing steel bar diameters curve, are displayed in Figures 2 and 3, respectively.

It is observed from Figure 2 that the yield strength increases with increasing strain rate for all reinforcing steel bar diameters except the 6-mm one, while this variation is lightly from 0.00223/s to 0.004478/s.

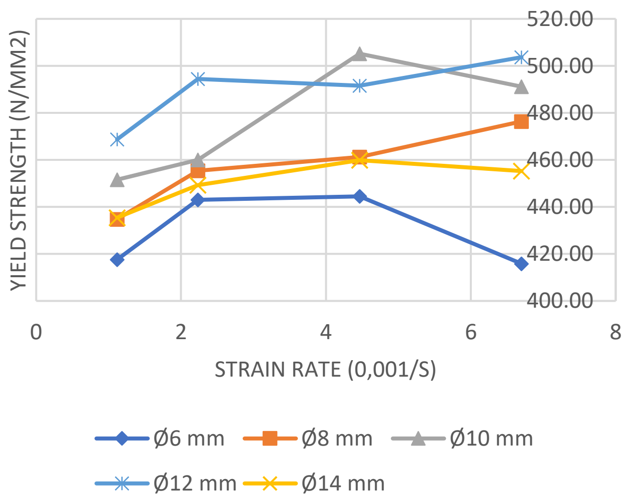


Figure 2 : Variations of yield strength of reinforcing steel bars with strain rate.

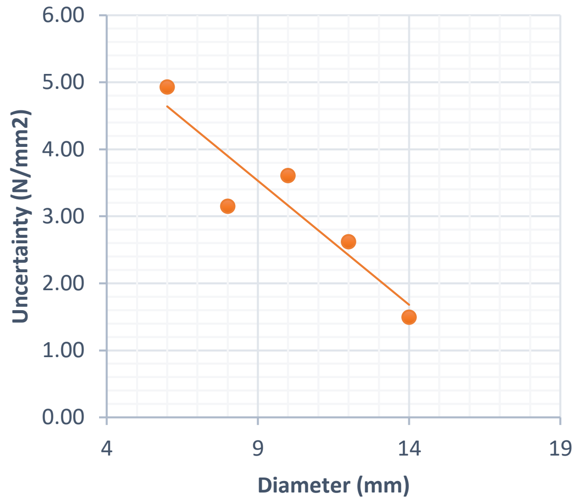


Figure 3 : Variations of uncertainty of reinforcing steel bars with their diameter – Yield Strength.

Another important observation is that the uncertainty seems to be affected by the reinforcing steel bar diameters. Indeed, from Figure 3 the uncertainty appears to decrease with the increasing of the reinforcing steel bar diameter. The last observation may justify the relatively high impact of strain rate variation on smaller reinforcing steel bar diameters.

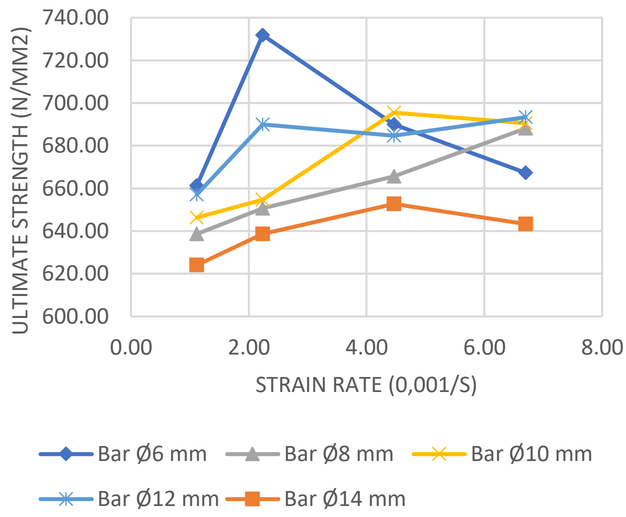


Figure 4 : Variations of ultimate tensile strength of reinforcing steel bars with strain rate.

Ultimate Tensile Strength

The ultimate tensile strength-strain curves for the reinforcing steel bars at various strain rates, and the uncertainty-reinforcing steel bar diameters curve, are displayed in Figures 4 and 5, respectively.

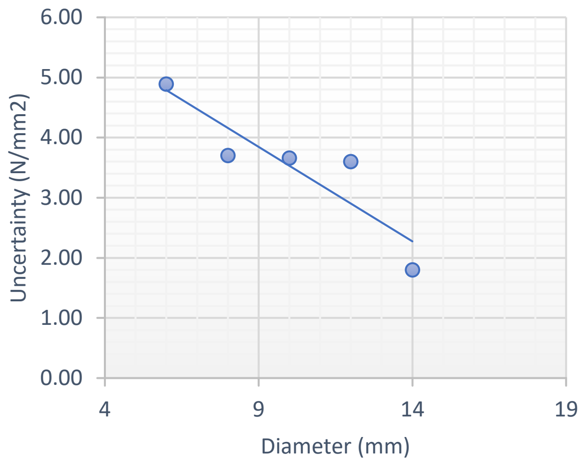


Figure 5 : Variations of uncertainty of reinforcing steel bars with their diameter – Ultimate Tensile Strength.

Figure 4 shows that in general the ultimate tensile strength increases with increasing strain rate; although for reinforcing steel bar of 6-mm diameter in size the variation is displayed in a non-uniform manner. Another tendency observed is that between 0.00447/s and 0.00670/s ultimate tensile strength seems to decrease lightly without affecting the general tendency. Likewise, for the yield strength, the uncertainty from ultimate tensile strength decreases with the increasing of the reinforcing steel bar diameters. This may be seen from Figure 5. The last observation may justify the relatively high impact of strain rate variation on smaller reinforcing steel bar diameters.

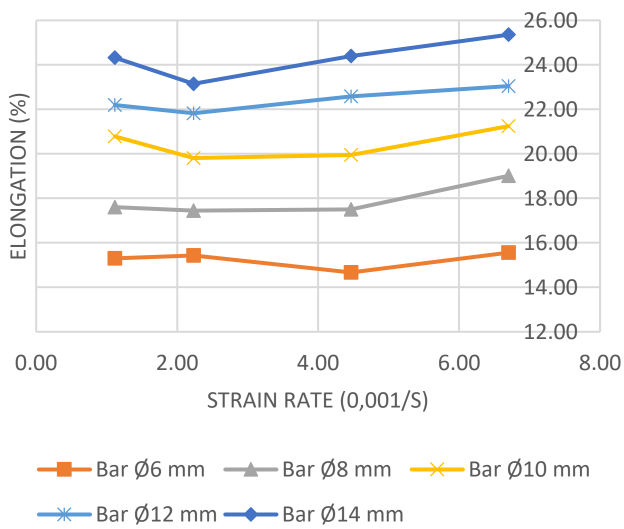


Figure 6 : Variations of elongation of reinforcing steel bars with strain rate.

Elongation

The elongation-strain curves for the reinforcing steel bars at various strain rates, and the uncertainty-reinforcing steel bar diameters curve, are displayed in Figures 6 and 7, respectively.

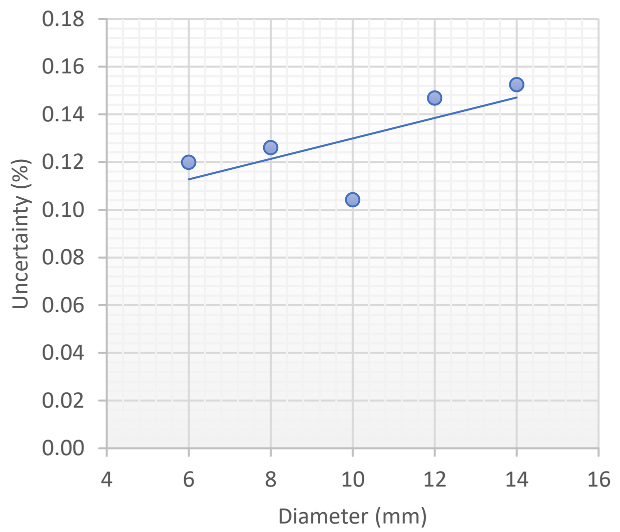


Figure 7 : Variations of uncertainty of reinforcing steel bars with their diameter – Elongation.

From Figure 6 it appears that the elongation is not much affected by strain rate increasing. In contrast to the yield strength and ultimate tensile strength, the uncertainty from elongation increases with the increasing of the reinforcing steel bar diameters. This may be seen from Figure 7.

Section Reduction

The section reduction-strain curves for the reinforcing steel bars at various strain rates, and the uncertainty-reinforcing steel bar diameters curve, are displayed in Figures 8 and 9, respectively.

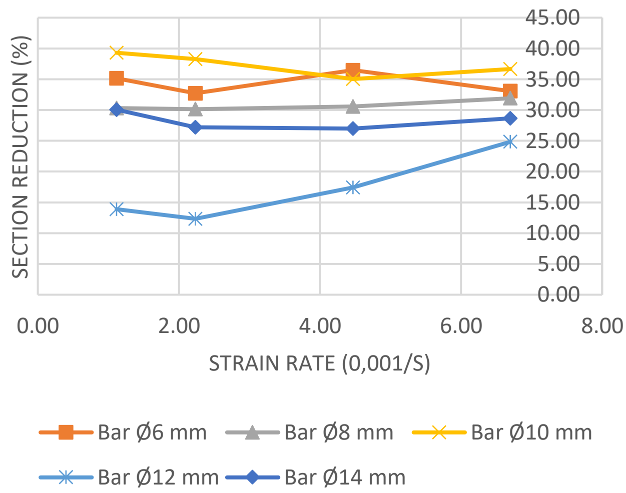


Figure 8 : Variations of section reduction of reinforcing steel bars with strain rate.

It is observed from Figure 8 that as the elongation, section reduction is not much affected by strain rate increasing, even though reinforcing steel bar of 12-mm diameter seems to be affected relatively more than the others. In contrast to the yield strength and ultimate tensile strength, the uncertainty from section reduction shows an apparent decrease with the increasing of the reinforcing steel bar diameters, unless one should notice that the values of the concerned parameter are in percentage in which the minimum and maximum are between 0.16 % (or 0.0016) and 0.39% (or 0.0039), respectively. The last assertion means that all uncertainties are less than 0.5%. Thus, it can be inferred that the uncertainty from section reduction is negligible. This may be seen from Figure 9.

Overview

All properties have been normalized using the quasi-static tests as a base. It can be seen that the strain at strain hardening is influenced by the low strain rate. The yield strength and the ultimate tensile strength were more affected by the change in the strain rate for the range of strain rates used in the test program. However, it is observed that strain rate has negligible effect on the elongation and section reduction of reinforcing

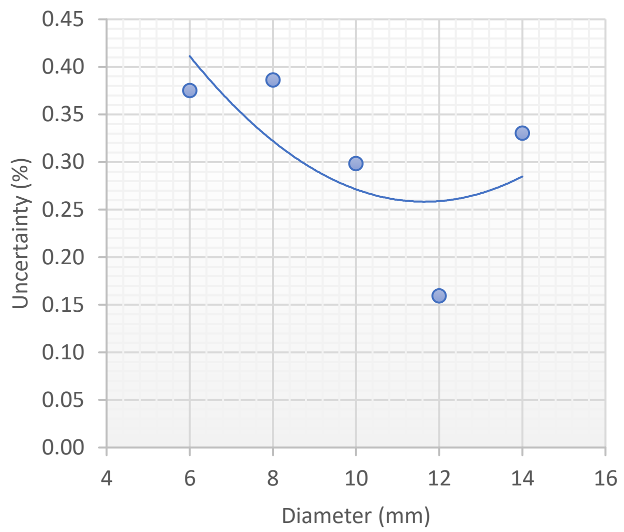


Figure 9 : Variations of uncertainty of reinforcing steel bars with their diameter – Section reduction.

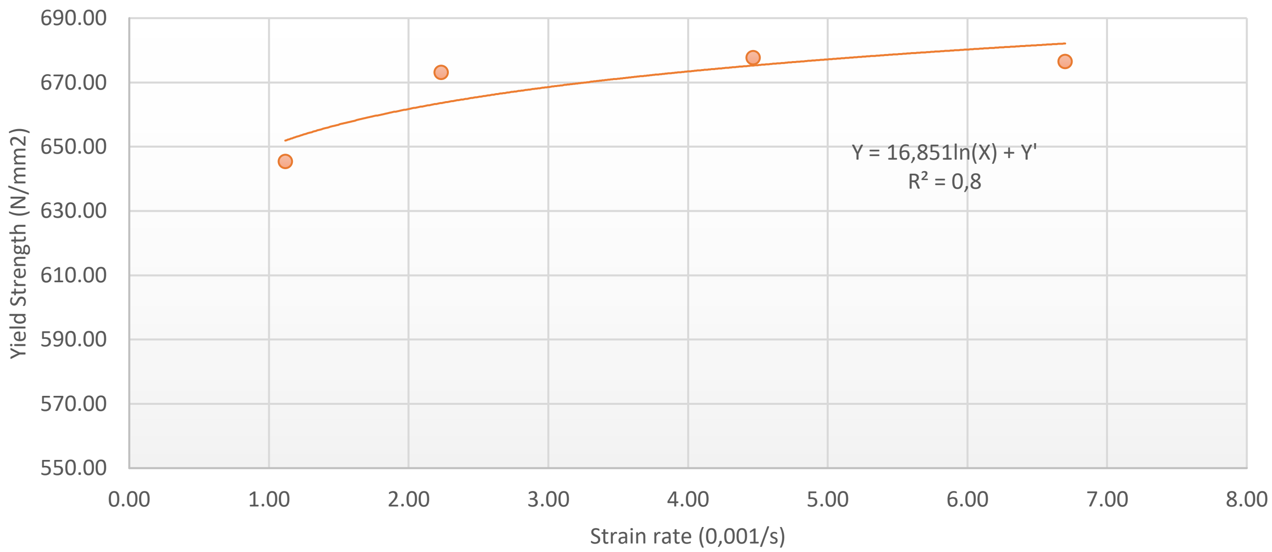


Figure 10 : Variations of Yield Strength of reinforcing steel bars with strain rate.

steel bars in the strain-hardening range. These results agree with early observations by [SOROUSHIAN and CHOI, 1987; FUJIMOTO et al., 1988; KASSAR and YU, 1992; MONJOINE, 1944; RESTREPO-POSADA et al., 1994; OBATA et al., 1996; GIONCU, 2000; SANCHEZ and PLUMIER, 2000; PENIN, 2010; DUNAND, 2013]. Unless, for the first two parameters for reinforcing steel bars of 6-mm diameter this conclusion seems not to be the case.

According to TANNOUS and SAADATMANESH [1998], the developments in the materials used, manufacturing technique, and quality control may have a serious impact on the properties of reinforcing steel bars products. This should also be account for uncertainty analysis.

The yield strength increased as the strain rate increased. The mean yield strength increased by 6.1% when the strain rate increased from 11.2 x 10-4/s to 67 x 10-4/s. The ultimate tensile strength of reinforcing steel bars increased also as the strain rate increased. This increase in ultimate tensile strength was less than the

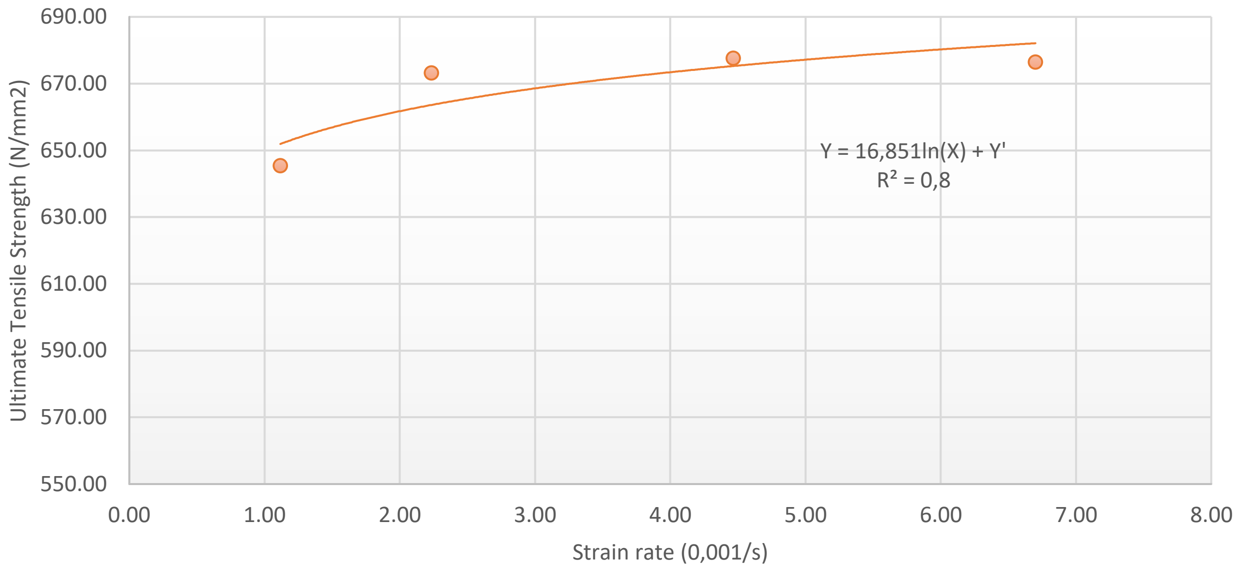


Figure 11 : Variations of Ultimate Tensile Strength of reinforcing steel bars with strain rate.

increase in yield strength of reinforcing steel bars. The mean tensile strength increased by only 4.8% when the strain rate increased from 11.2 x 10-4/s to 67 x 10-4/s.

Based on the results throughout the current study, regression models are proposed both for yield strength and ultimate tensile strength from the results of all tests, and presented along with best-fit logarithmic regression lines in Figures 10 and 11. These two Figures (10 and 11) are the results of common tendency for yield strength and ultimate tensile strength, respectively, for all data from the four companies steel bars.

The formula (7) is proposed in order to take into account the low strain rate effect on both yield strength and ultimate tensile strength:

$$\boldsymbol{Y = 16.851\ln(\dot{e}_{L_c}) + Y'} \qquad (7)$$

Where:

- Y : can be replaced by unknown yield strength or unknown ultimate tensile strength,
- Y' : can be replaced by known yield strength or known ultimate tensile strength,
- $\dot{e}_{L_c}$: estimated strain rate over the parallel length.

This regression model seems to be a well representative of the general tendency with an "R squared" of 80%. This formula should be used as a means by which some quick verifications and checking may be archived.

CONCLUSION

Based on the test results obtained, the following observations can be drawn on the effect of low strain rate in on the uniaxial mechanical properties of reinforcing steel bars:

- ✓ Even in range of low strain rate, the effect of strain rate can cause relative increases in yield strength and ultimate tensile strength of reinforcing steel bars.
- ✓ The effect of strain rate appears to be inconsistent on the yield strength and ultimate tensile strength of reinforcing steel bars of 6-mm diameter.
- ✓ The elongation and section reduction of reinforcing steel do not appear to be substantially affected by the strain rate.

Finally, a new regression formula is proposed for both yield strength and ultimate tensile strength with a "R squared" of 80%. This formula should be used as a means by which some quick verification and checking may be archived.

Further testing is required to investigate the effect of low strain rate reinforcing steel bars properties. In particular, information is required on the following:

- ✓ The low strain rate effects on bigger reinforcing steel bars such as 18, 20, 22, 32-mm diameters.
- ✓ The metallurgical and chemical composition influence at low strain rate effects of reinforcing steel bars.
- ✓ The combined effects of low strain rate and high temperature on the monotonic behavior of reinforcing steel.

RESUME

Influence de la variation des faibles vitesses de déformation sur les paramètres de l'essai de traction uni-axiale des barres de fer.

Cette étude traite de manière expérimentale le comportement des paramètres d'essai de traction uni-axiale des barres de fer sous l'influence des différentes faibles vitesses de déformation, quasi-statiques, comprises entre 0,001 12 s^{-1} et 0,006 70 s^{-1}. L'objectif principal de ces essais était de donner une indication de l'effet de la variation de faible vitesse de déformation sur les courbes d'essais uni-axiales, monotones, Contrainte-Déformation, Allongement-Déformation, Réduction section-Déformation, des barres de fer. Les résultats des essais de traction indiquent que la limite d'élasticité et la résistance à la traction des barres de fer testées augmentent dans le même sens que la variation de la vitesse de déformation dans la plage qualifiée de « faible » ; tandis que l'allongement et la réduction de section des barres en acier sont sensiblement moins affectés par cette variation. Il a également été observé que les barres de fer des faibles diamètres étaient plus affectées par la variation de faible vitesse de déformation, bien que parfois de manière non consistante. Ainsi donc, il est recommandé d'être très prudent lors du test de barres d'acier d'armature des faibles diamètres. En outre, une nouvelle formule de régression est proposée pour prendre en compte cette variation de la limite d'élasticité et celle de la résistance à la traction, avec un coefficient de détermination appelé aussi « R-squared » de 80%. Cette formule pourra servir à de vérifications rapides de manière efficace.

Mots Clés:
Limite Elastique, Ultime, Traction, Reduction de la Section, Contrainte, Allongement, and Congo.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Serge Kisambese for his logistic and technical assistance. The writers are grateful to the head of the Civil Engineering Department of University of Kinshasa, Professor Rosemond Tozin, for his technical support. The writers would also like to thank the technical staff at the Polytechnic Faculty of Kinshasa for their dedication and thoroughness.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

WARNING

The authors decline all responsibilities for using any information from this study for other purposes than the current one.

REFERENCES

BOYCE B.L., DILMORE M.F. [2009]. The dynamic tensile behavior of tough, ultrahigh-strength steels at strain-rates from 0.0002 s–1 to 200 s–1. Int. J. Impact Eng. 36, 263–271.

BS EN 10002-1. [2001]. Metallic materials – tensile testing. Part 1: method of test at ambient temperature. Brussels : European Committee for Standardization.

CADONI E., SINGH N.K., FORNI D., SINGHA M.K., GUPTA N.K. [2016]. Strain rate effects on the mechanical behavior of two Dual Phase steels in tension. Eur. Phys. J. Spec. Top. 225, 409–421.

DAVIS E.A. [1938]. The effect of speed of stretching and the rate of loading on the yielding of mild steel. Journal of Applied Mechanics 5 (4) A137-A140.

DUNAND M. [2013]. Effect of strain rate on the ductile fracture of Advanced High Strength Steel Sheets: Experiments and modeling. PhD thesis, Polytechnique.

FILIATRAULT A., HOLLERAN M. [2001]. Stress-strain behavior of reinforcing steel and concrete under seismic strain rates and low temperatures. Mater. Struct., 34-5, 235– 239.

FROLI M., ROYER-CARFAGNI G. [1999]. Discontinuous deformation of tensile steel bars: experimental results. ASCE J. Eng. Mech. 125(11), 1243–1250.

FUJIMOTO M., NARUBA T., SASAKI S. [1988]. Strength and deformation capacity of steel brace under high-speed loading. Proceedings of the 9th World Conference on Earthquake Engineering, Tokyo-Kyoto, Vol. IV, 139-144.

GEIGER M., MERKLEIN M., KAUPPER M. [2008]. Investigation of the mechanical behavior of advanced high strength steels under various loading conditions. Int. J. Mater. Form. 1, 225–228.

GIONCU V. [2000]. Influence of strain-rate on the behavior of steel members. Proceedings of the Third International Conference STESSA 2000, Montreal, Canada 19-26.

ISO 6892-1. [2016] Metallic Materials-Tensile Testing Part 1: Method of test at room temperature British Standard Institution

KASSAR M., YU W.W. [1992]. Effect of strain-rate on material properties on sheet steels. Journal of Structural Engineering 118 (11) 3136-3150.

KIRUMBA M.K., RICARDO R.V. [2019]. Investigation of conformity of Reinforcing Steel Bars Used in Kinshasa Construction Industry. Congosciences. 7(1), 1-10.

LOVEDAY M.S., GRAY T., AEGERTER J. [2004]. Tensile testing of metallic materials: A review, Final report of the TENSTAND project of work package.

MISHRA A., MARTIN M., THADHANI N. N., KAD B.K., KENIK E.A., MEYERS M.A. [2008]. High-strain-rate response of ultra-fine-grained copper. Acta Mater.56, 2770–2783.

MONJOINE M.J. [1944]. Influence of rate of strain and temperature on yield stress of mild steel. Journal of Applied Mechanics 11, 211-218.

OBATA M., GOTO Y., MATSURA S., FUJIWARA H. [1996]. Ultimate behavior of tie plates at high-speed tension. Journal of Structural Engineering 122 (4) 416-422.

PENIN A. [2010]. Etude sous chargement dynamique biaxial d'une tôle enacierDP450: influence sur le comportement et la formabilité. PhD thesis, Université de Bretagne Sud.

RESTREPO-POSADA J.1., DODD L.L., PARK R., COOKE N. [1994]. Variables affecting cyclic behavior of reinforcing steel. Journal of Structural Engineering 120 (11) 3178-3196.

SANCHEZ L., PLUMIER A. [2000]. Tests on the strain rate effects on beam-to-column steel connection. Proceedings of the Third International Conference STESSA 2000, Montreal, Canada 247-254.

SOROUSHIAN P., CHOI K. [1987]. Steel mechanical properties at different strain rated. Journal of Structural Engineering 113 (4) 863-872.

SUO T., CHEN Y.Z., LI Y.L., WANG C.X., FAN X.L. [2013]. Strain rate sensitivity and deformation kinetics of ECAPed aluminum over a wide range of strain rates. Mater. Sci. Eng. A. 560, 545–551.

TANNOUS F.E., SAADATMANESH H. [1998]. Environmental effects on the mechanical properties of E-glass FRP rebars. ACI Mater. J. 95(2), 87–100.

WAKABAYASHI M., NAKAMURA T., IWAI S., HAYASHI Y. [1984]. Effects of strain rate on the behavior of structural members. Proceedings of the 8th World Conference on Earthquake Engineering, San Francisco, CA, Volume IV, 491-498.

WEI Q. [2007]. Strain rate effects in the ultrafine grain and nanocrystalline regimes-Influence on some constitutive responses. J. Mater. Sci. 42, 1709–1727.

WEI Q., KECSKES L., JIAO T., HARTWIG K.T., RAMESH K.T., MA E. [2004]. Adiabatic shear banding in ultrafine-grained Fe processed by severe plastic deformation. Acta Mater. 52, 1859–1869.

XIONG R.G., FU R.Y., SU Y., LI Q., WEI X.C., LI L. [2009]. Tensile Properties of TWIP Steel at High Strain Rate. J. Iron Steel Res. Int. 16, 81–86.

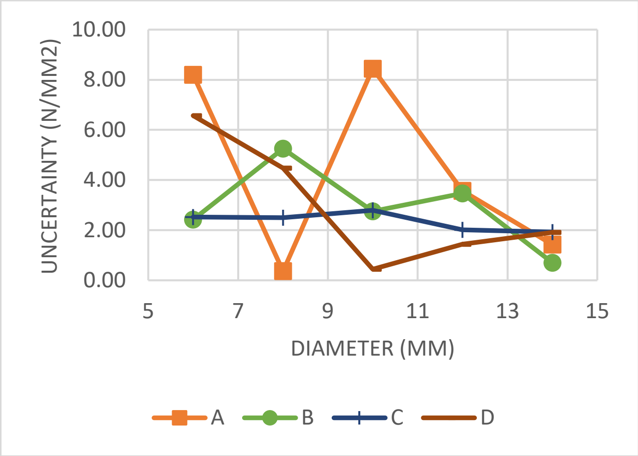
YU H.D., GUO Y.J., LAI X.M. [2009]. Rate-dependent behavior and constitutive model of DP600 steel at strain rate from 10−4 to 103 s−1. Mater. Des. 30, 2501–2505.

YUAN F.P., CHEN P., FENG Y.P., JIANG P., WU X.L. [2016]. Strain hardening behaviors and strain rate sensitivity of gradient-grained Fe under compression over a wide range of strain rates. Mech. Mater. 95, 71–82.

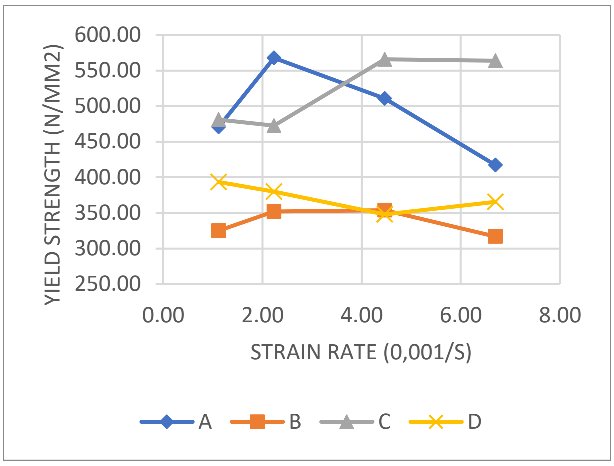
ZHANG H., LI H.N., LI C., CAO G.W. [2018]. Experimental and numerical investigations on seismic responses of reinforced concrete structures considering strain rate effect. Constr. Build. Mater. 173, 672–686.

APPENDICES

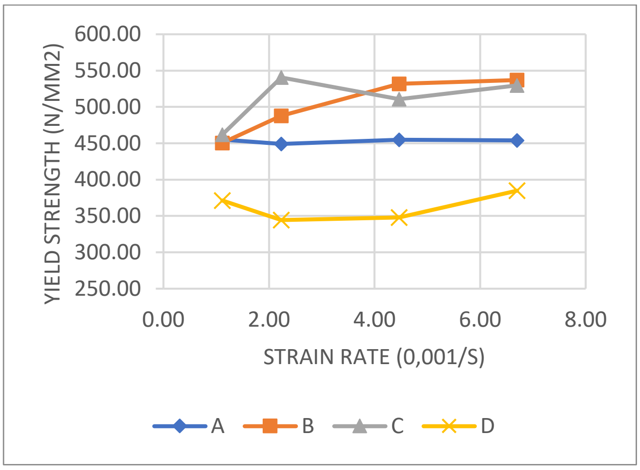
A. Yield Strength



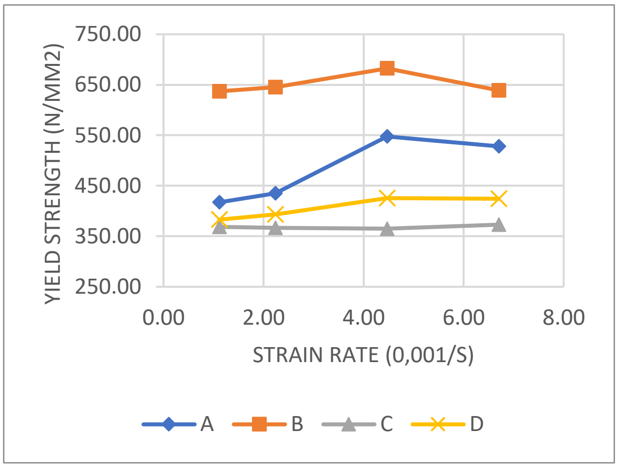
A.1.



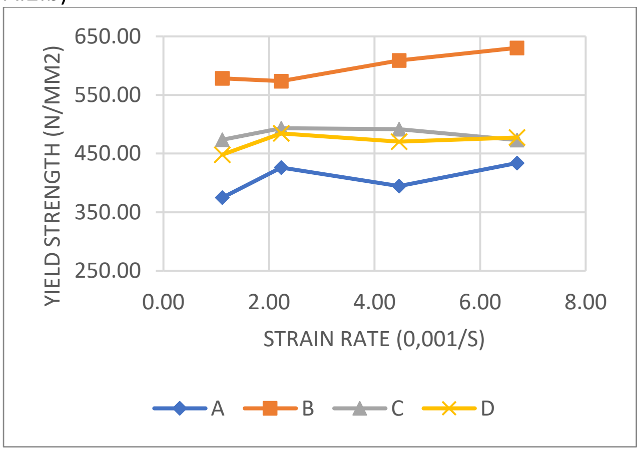
A.2.a)



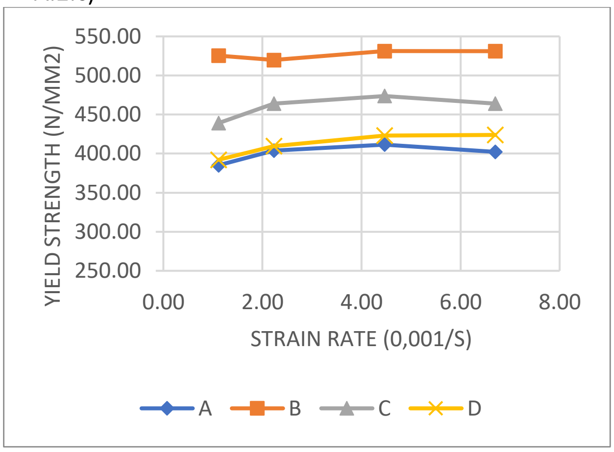
A.2.b)



A.2.c)



A.2.d)

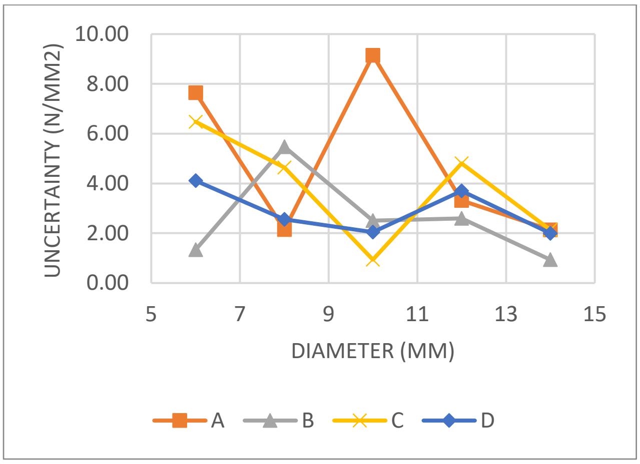


A.2.e)

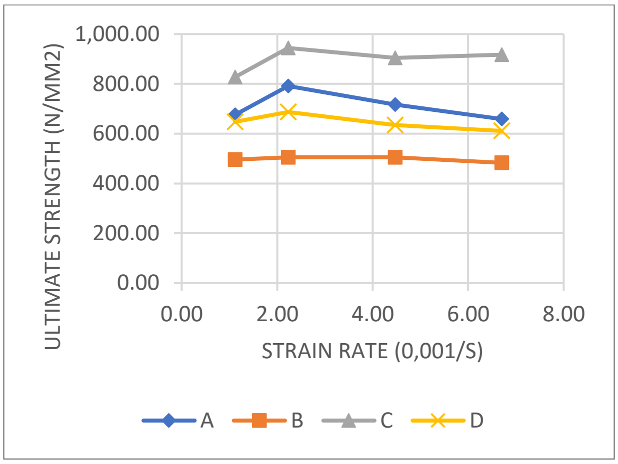
Figures A.1. Variation of Yield strength Uncertainty with steel bar diameter based on average from different Strain Rates; A.2. Yield Strength versus Strain Rate: a) Steel Bars Ø6 mm; b) Steel Bars Ø8 mm; c) Steel Bars Ø10 mm; d) Steel Bars Ø12 mm; e) Steel Bars Ø14 mm.

Note: A, B, C, and D represent the four (4) companies which products were tested.

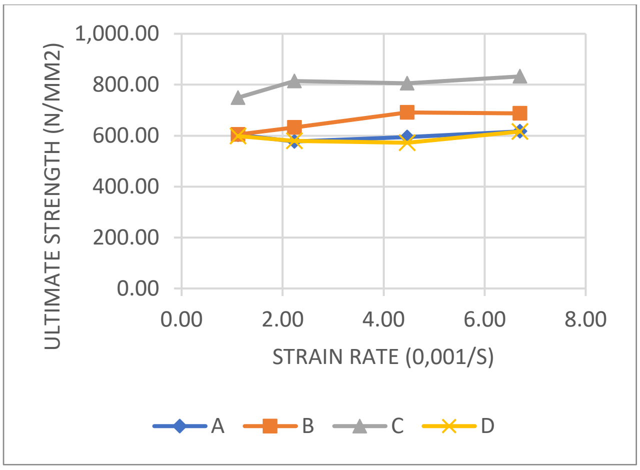
B. Ultimate Tensile Strength



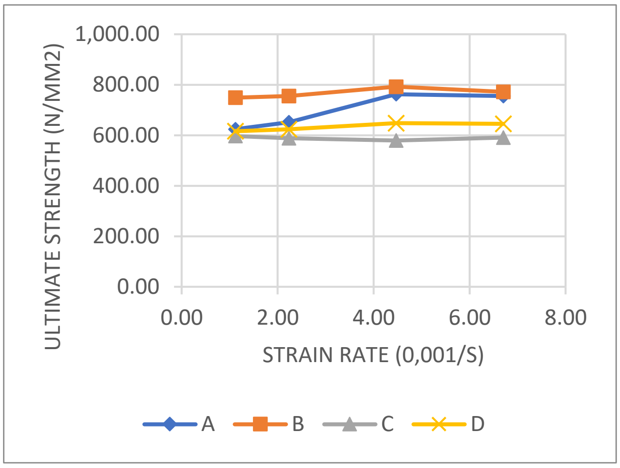
B.1.



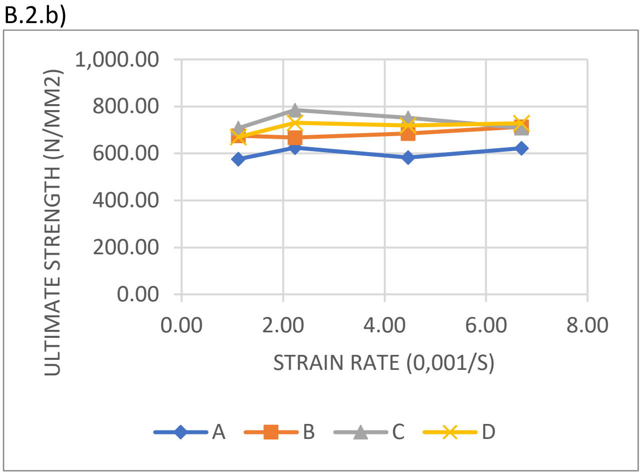
B.2.a)



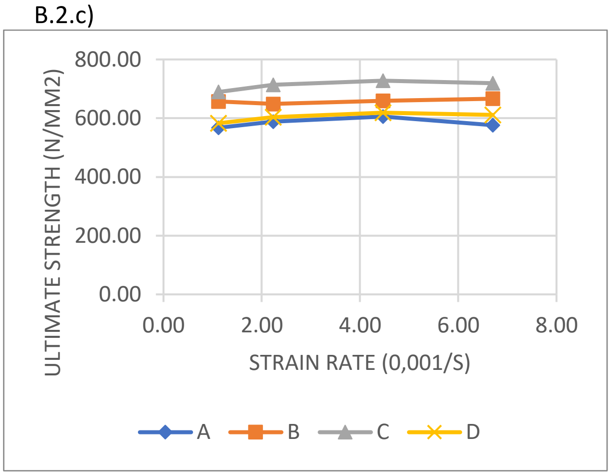
B.2.b)



B.2.c)



B.2.d)

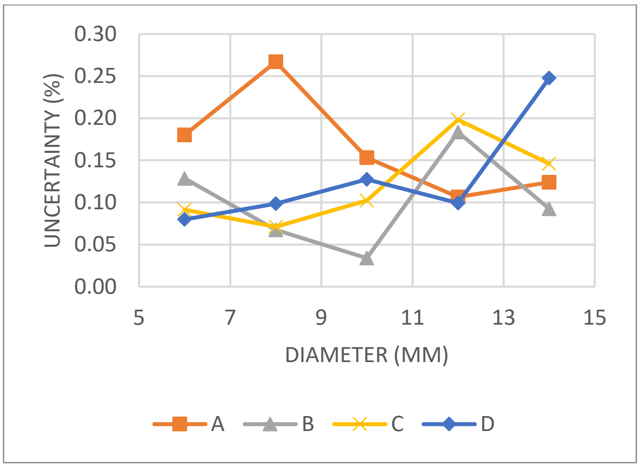


B.2.e)

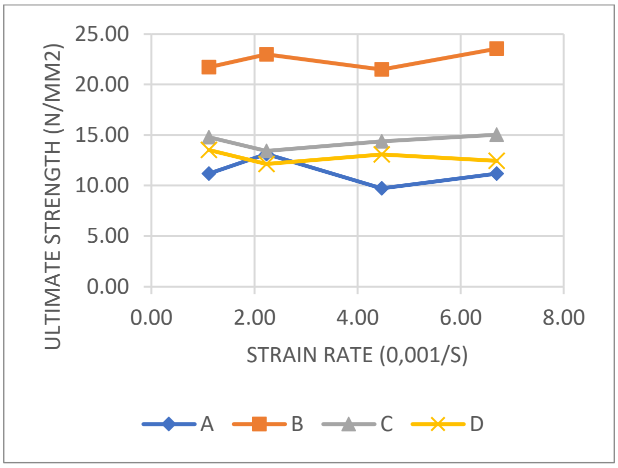
Figures B.1. Variation of ultimate tensile strength uncertainty with steel bar diameter based on average from different Strain Rates; B.2. Ultimate Tensile Strength versus Strain Rate: a) Steel Bars Ø6 mm; b) Steel Bars Ø8 mm; c) Steel Bars Ø10 mm; d) Steel Bars Ø12 mm; e) Steel Bars Ø14 mm.

Note: A, B, C, and D represent the four (4) companies which products were tested.

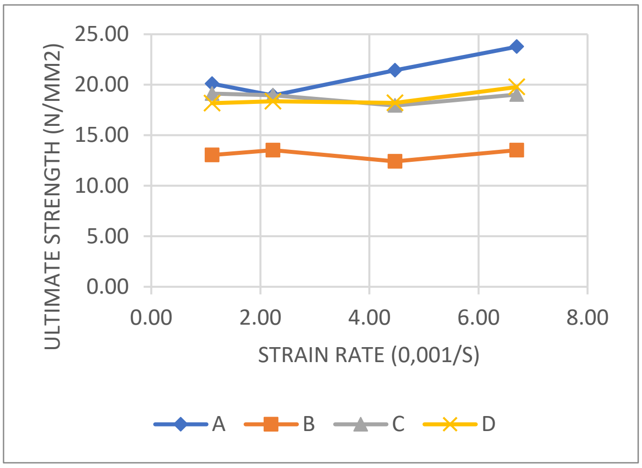
C. Elongation



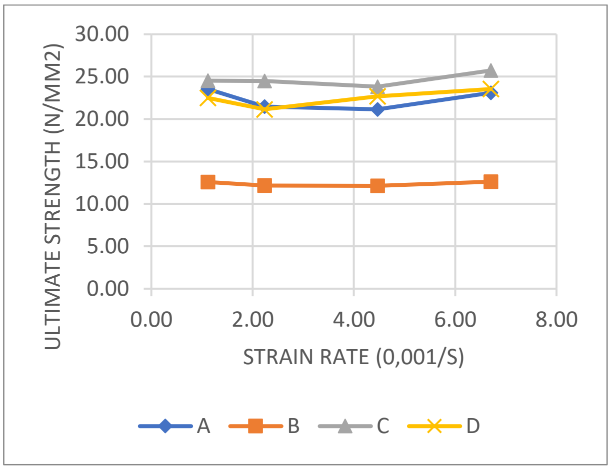
C.1.



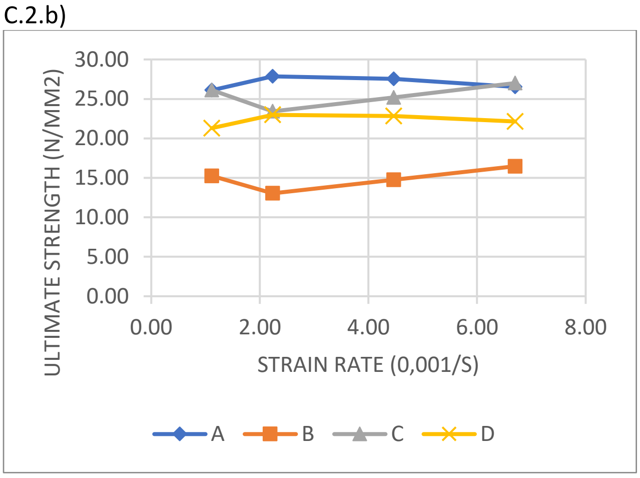
C.2.a)



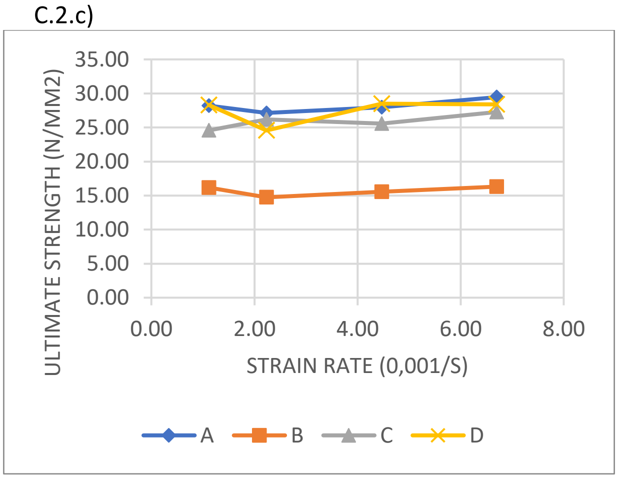
C.2.b)



C.2.c)



C.2.d)

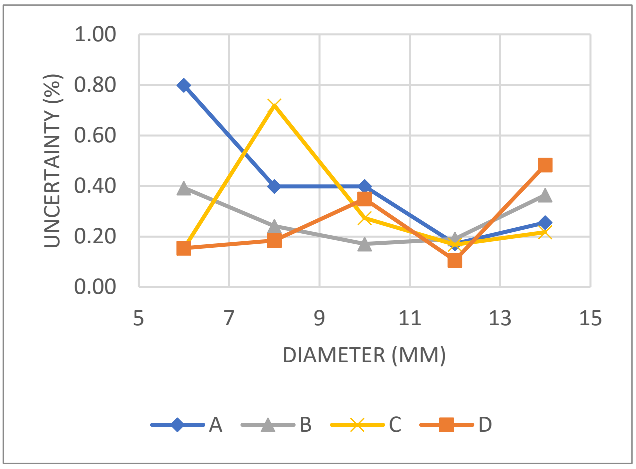


C.2.e)

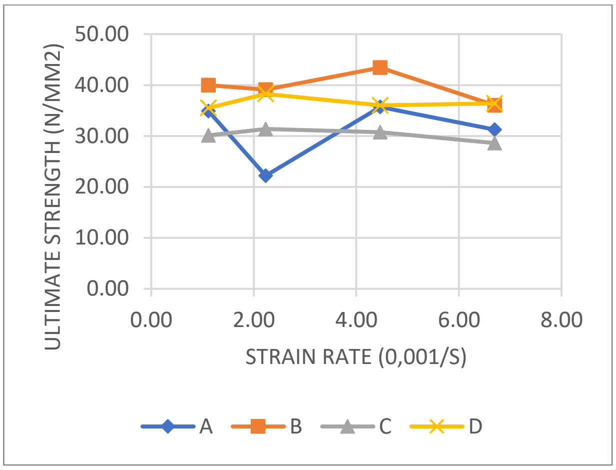
Figures C.1. Variation of elongation uncertainty with steel bar diameter based on average from different Strain Rates; C.2. Elongation versus Strain Rate: a) Steel Bars Ø6 mm; b) Steel Bars Ø8 mm; c) Steel Bars Ø10 mm; d) Steel Bars Ø12 mm; e) Steel Bars Ø14 mm.

Note: A, B, C, and D represent the four (4) companies which products were tested.

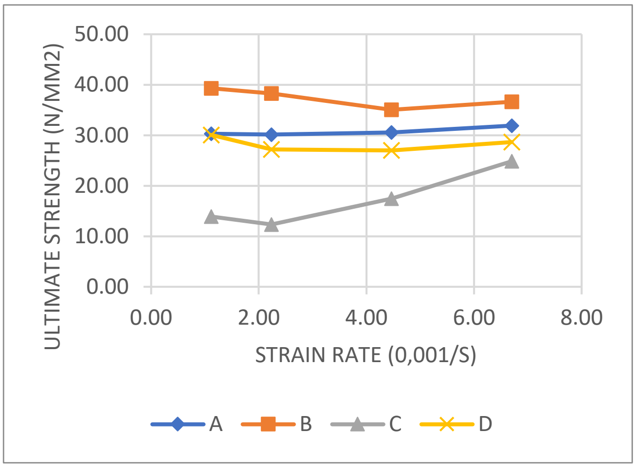
D. Section Reduction



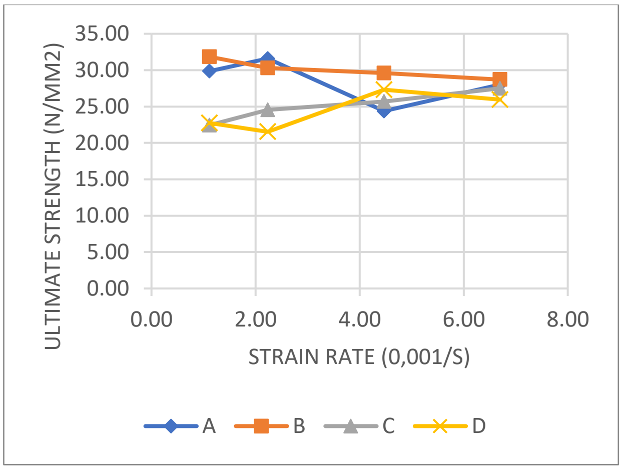
D.1.



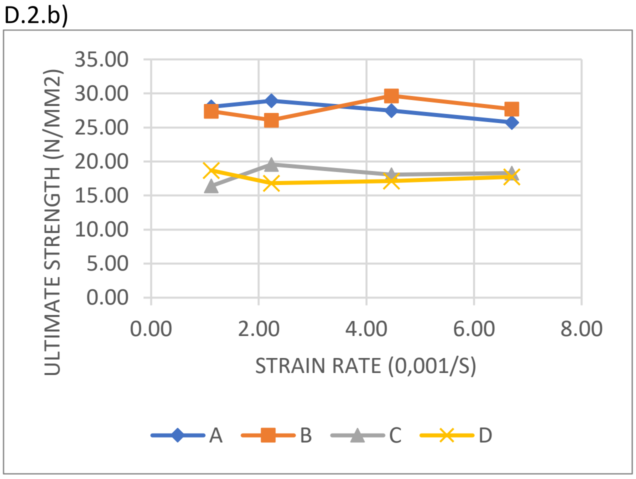
D.2.a)



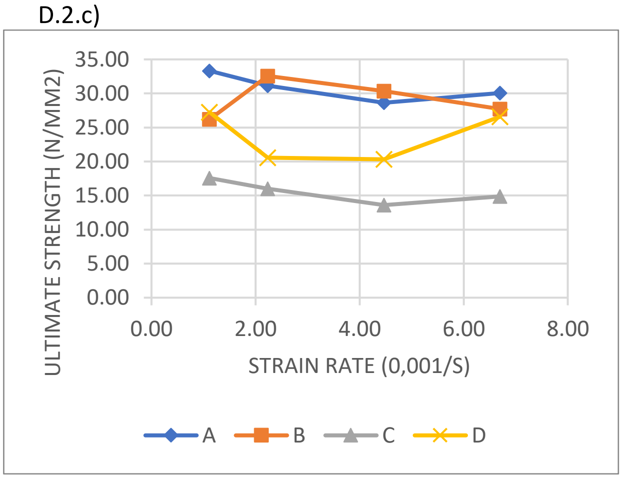
D.2.b)



D.2.c)



D.2.d)



D.2.e)

Figures D.1. Variation of section reduction uncertainty with steel bar diameter based on average from different Strain Rates; C.2. Section Reduction versus Strain Rate: a) Steel Bars Ø6 mm; b) Steel Bars Ø8 mm; c) Steel Bars Ø10 mm; d) Steel Bars Ø12 mm; e) Steel Bars Ø14 mm.

Note: A, B, C, and D represent the four (4) companies which products were tested.