Performance of High-Strength Steel Reinforcing Bars under Low-Velocity Impact

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Abstract: With the increasing need for sustainable building practices, there is a high demand in using high-strength steel (HSS) bars in reinforced concrete (RC) structures. Utilising HSS can reduce the amount of rebar in RC structures because the area of steel required to achieve a target design capacity is inversely proportional to its yield strength, leading to better field inspection, easier concrete placement, and reducing steel congestion, construction time and associated costs. The reduction in steel mass can be especially beneficial in structures designed to resist high loading rate events, in which increased amount of steel is required to strengthen the impact area. From the other side, AS 3600:2018 allows the use of longitudinal steel rebar up to 600MPa for limit state design, and fitments up to 800MPa. Yet, little research has been conducted on the overall performance of high-strength reinforcing steels, mainly Grades 600 and 750, under high strain rate loading. This paper reports the results of the experimental low-velocity impact tests conducted on tensile coupons taken from the core of Grades 500, 600 and 750 reinforcing bars. Various strain rates ranging from 10^{-3} /s to 10/s have been considered in the experimental program. The experimental results indicate the sensitivity of the dynamic increase factor of yield and ultimate stresses as well as uniform strain, and ultimate stress to yield stress ratio to strain rate. The outcomes of this paper have the potential to be incorporated in current codes of practice and used for calibration of constitutive material models.

Keywords: high-strength steel, reinforcing bar, impact, experimental tests

1 Introduction

With reinforced concrete being one of the most popular and commonly used composite materials used in many buildings today for its durability and economical cost, engineers have further improved its concept with the introduction of high-strength steel (HSS) rebars, with nominal yield strength (f_y) of f_y> 500MPa, to replace the conventional **n**ormal-**s**trength **s**teel (NSS) rebar with nominal yield strength of f_y≤ 500MPa. This is not only because of higher capacity demand for structures, but the need for sustainability, HSS rebars allow for lower transportation costs, lower raw material and energy use for production and better fitments due to smaller member sizes allowing less congestion as opposed to conventional NSS rebars (1).

Prior to 2013, in the United States, the use of steel reinforcement in concrete structures was limited to steels with yield strength of 517MPa. After the interim revision of the AASHTO LRFD Bridge Design Specifications, several sections were changed to allow for the use of HSS reinforcement with yield strength up to 689MPa (2). Changes to the Australian standards have also been made in the past few years to recognise the use of higher-grade steel. The most recent AS3600 (3) allows for the use of reinforcing steels up to 600MPa, and for concrete column fitments up to 800MPa, except for concrete walls where the yield strength of reinforcing steel should not exceed 500MPa.

On the other hand, in the rise of global tensions and threat of terrorism, more concerns have been raised regarding the safety of buildings and infrastructures subjected to impact loading which can significantly compromise the structural integrity of concrete buildings and infrastructures. Yet, the amount of research data on performance of HSS rebars under high-strain rate loading is very limited. The available research has mainly focused on mechanical properties of **n**ormal-**s**trength **s**teel (NSS) rebar with nominal yield strength of f_y≤ 500MPa. Cadoni and Forni (4) conducted an experimental study on cylindrical dog bone specimens taken from B500 rebars under high-strain rates of 10/s to 1000/s where it was shown that the mechanical properties of B500 rebar is sensitive to strain rate. Lin et al. (5) compared different rebars with nominal yield strength of f_y = 235, 335, 400 and 500 MPa, that are commonly used in China, under varying strain rates ranging from 2/s to 80/s. It was found that both yield strength (f_y) and ultimate strength (f_u) of all rebars increased with increase of strain rates; however, when f_y increases, the increase in value of dynamic increase factor (denoted as DIF and defined as the ratio of mechanical properties under high-strain rate to the corresponding value under quasi-static conditions) reduces, thereby suggesting lower sensitivity of rebars with higher f_y to the strain rate. This had similarly been reported by Malvar (6) in which various rebars ranging from 290 to 710 MPa were compared under high-strain rate loading and it was concluded the value of DIF for yield and ultimate strength would increase with lowering yield strength. However, this study mainly focused on variations of yield and ultimate stresses and did not provide detailed analysis on changes of other mechanical properties of HSS rebars with strain rate.

In addition to the yield strength and ultimate strength, the parameters associated with the ductility of the steel material (e.g. uniform strain, fracture strain, ultimate strength (f_u) to yield strength (f_y) ratio) may also be affected by high-strain rate loading. Cadoni and Forni (7) reported the mechanical properties of cylindrical steel dog bone samples taken from 690MPa steel plates under strain rates of 3, 30, 250, 450 and 950 /s strain rates. It was shown that the ultimate strength to yield strength ratio (f_u/f_y) decreases as strain rate increases. Note that f_u/f_y is an important ratio as many standards introduce a minimum value for f_u/f_y ratio as one of the prescribed parameters addressing ductility of reinforcing steel. For example, in accordance with AS4671 (8), the minimum f_u/f_y ratio for 500MPa and 600MPa rebars with normal ductility (Class N) should be 1.08, and that of 750MPa rebars should be 1.04.

This paper deals with experimental tensile tests under high-strain rate loading ranging from 10^{-3} /s to 10/s conducted on the samples taken from HSS rebars with nominal yield strength of f_y= 600MPa and 750MPa. Similar tests have also been conducted on the NSS rebars; the results of which are compared with those obtained from HSS rebars tests. The variations in yield and ultimate stresses as well as uniform strain and f_u/f_y with strain rate are discussed.

2 Specimen geometry

The geometry of the cylindrical dog bone shape specimens taken from each rebar is shown in Figure 1. The ends of each specimen have been threaded to improve gripping conditions and ensure the deformation and failure mainly occur within the gauge length. It is worth mentioning that the nominal diameters of 500MPa, 600MPa and 750MPa rebars considered in this study were 12mm, 16mm and 13.1mm, respectively. Using in-house CNC machine available at Monash University, the dog bone shape specimens were taken in a way that the section of the gauge length coincides the core of each rebar. The dimensions of each specimen were kept the same among HSS and NSS rebars in order have a fair comparison between all of them.

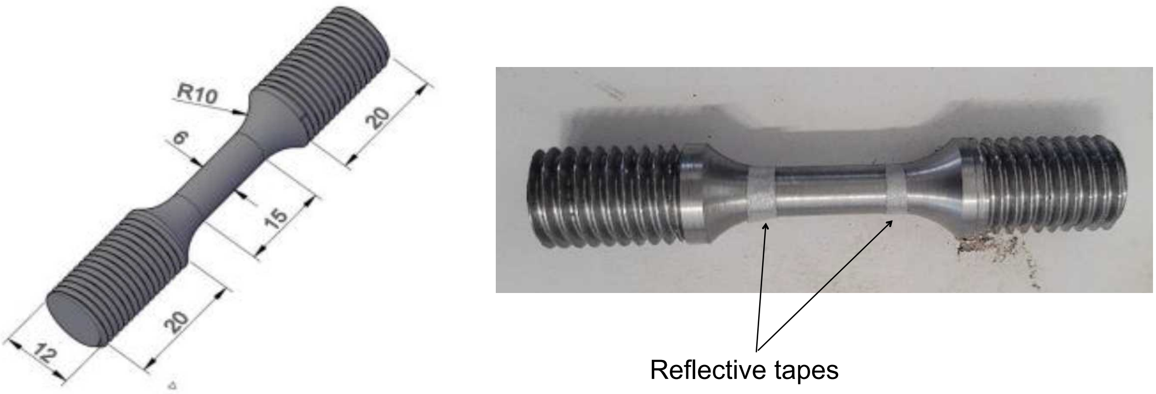


Figure 1. (a) The geometry of the cylindrical dog bone shape specimen (b) An actual specimen showing reflective tapes on the gauge length (all dimensions in mm)

3 Experimental equipment

The Instron 8802 servo-hydraulic testing machine (Fig. 2a) was used to conduct quasi-static and low-velocity impact tensile tests on the coupons taken from the rebars. The testing machine can apply tensile load on the specimen at a defined cross-head speed. The maximum cross-head speed is 150mm/s. A compressive load equivalent to a small percentage of the specimen's elastic buckling load was firstly applied manually to the specimen. Thus, the high-strain rate tensile test was subsequently performed. This loading scenario is to resolve the inherent issue related to the testing machine delay in reaching the defined cross-head speed, and ensure the specimen experiences full cross-head speed throughout the high-strain rate tensile test. In this study, the desired quasi-static strain rate of 0.001/s, and high-strain rates of 5 and 10/s were achieved when the cross-head speed was defined as 0.015mm/s, 75mm/s and 150mm/s, respectively.

In addition to the force and cross-head position, the displacement of each specimen was measured using an MTS LX500 laser extensometer (Fig. 2b). This non-contact laser extensometer measures the distance between two reflective tapes attached to the specimen (the reflective tapes are shown in Fig. 1b). Hence, the engineering strain can be calculated via dividing the extensometer's measurement by the initial distance between the reflective tapes. The initial distance between the reflective tapes varies among tested specimens; however, it was tried to keep it as close as possible to the gauge length (i.e.

15mm) shown in Fig. 1a. Finally, the engineering stress-strain curves or desired mechanical properties can be drawn using the data obtained from these experiments.

Figure 2. (a) Instron 8802 servo-hydraulic testing machine used for quasi-static and low-velocity impact tests (b) MTS LX500 laser extensometer used to measure the displacement of each specimen

4 Results and discussion

4.1 Quasi-static results

Figure 3 shows the engineering stress-strain curves obtained from the quasi-static tests conducted on the coupons taken from 500MPa, 600MPa and 750MPa rebars. A distinct yielding plateau can be seen for 500MPa and 600MPa bars. Importantly, the measured yielding strength for 500MPa and 600MPa bars seems to be less than their nominal values. This is mainly due to the fact the tensile tests in this study were conducted on the samples taken from the core of the specimen. During manufacturing procedure, the rebars undergo different straightening processes causing a non-uniform strain distribution over their cross-section. Hence, the samples taken from the core of rebars may exhibit different mechanical properties from the nominal values and those obtained from the whole bars' tests. Nevertheless, this does not affect the objective of this study which aims to conduct a comparative study to explore the effect of steel grade on mechanical properties of rebars under high-strain rate loading.

It is seen from Figure 3 that the values of uniform strain (i.e. strain corresponding to the ultimate stress) and engineering fracture strain reduce as the nominal yield strength of rebar increases. Moreover, the f_u/f_y ratio of 500MPa, 600MPa and 750MPa rebars under quasi-static loading is 1.33, 1.31 and 1.09, respectively. These are indicative of the fact that the HSS rebars (particularly 750MPa rebars) are noticeably less ductile than NSS rebars.

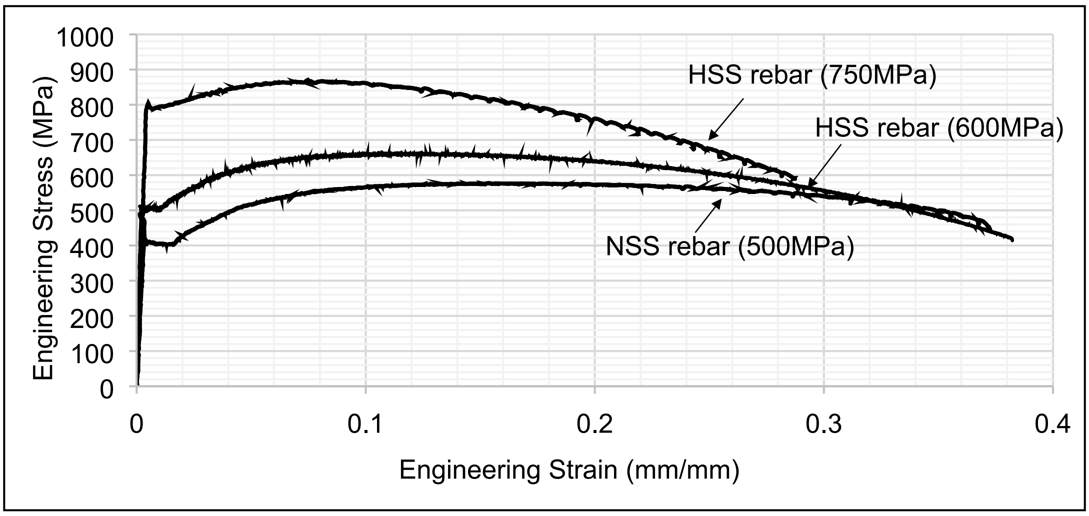


Figure 3. Engineering stress-strain curves for NSS and HSS rebars under quasi-static loading

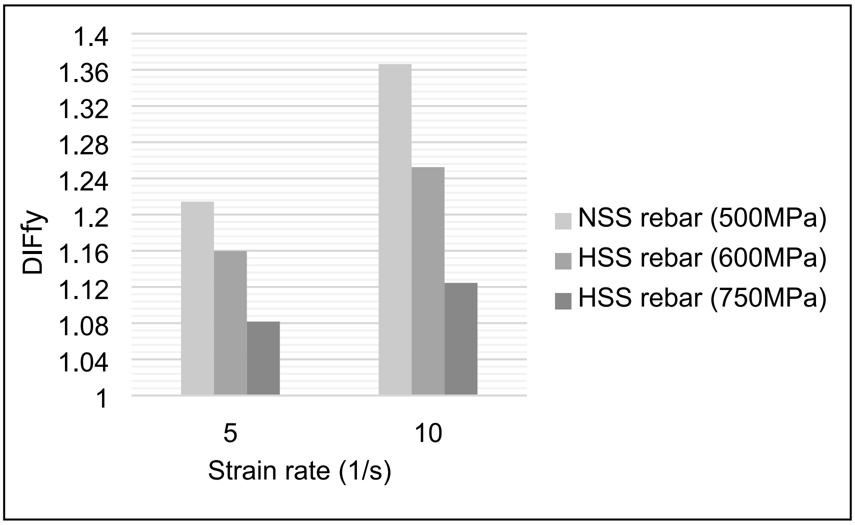
4.2 Low-velocity impact test results

The experimental results obtained from the low-velocity impact tests conducted on HSS and NSS rebars are discussed in this section.

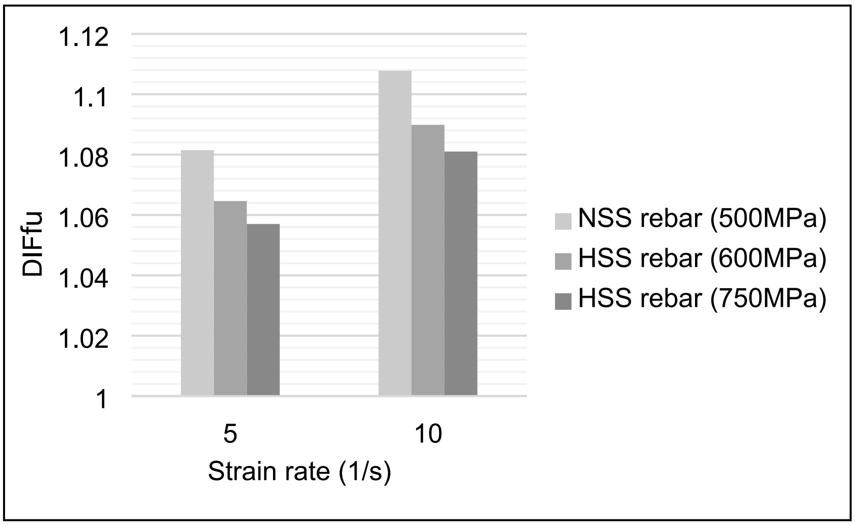
4.2.1 Strength

Figure 4 shows the variations of dynamic increase factor (DIF) for yield and ultimate stresses of tested rebars, denoted as DIF_{fy} and DIF_{fu}, respectively. It seen for all steel grades, the yield and ultimate strengths of rebars increase when the strain rate increases. However, the sensitivity of DIF_{fy} and DIF_{fu} values to strain rate reduces with the increase of nominal yield strength for which the DIF_{fy} values corresponding to the 750MPa, 600MPa and 500MPa bars under strain rate of 10/s are, respectively, 1.12, 1.25 and 1.36. Additionally, the DIF_{fu} values corresponding to the ultimate strength exhibit less variations with steel grades. For example, as shown in Fig. 4b, the DIF_{fu} values corresponding to the 750MPa, 600MPa and 500MPa bars under strain rate of 10/s are, respectively, 1.08, 1.09 and 1.10.

The above-mentioned observation indicates that under high strain rate loading the stress required to induce plastic deformation of the material increases. This increase is because dislocations (known as linear topological defects within the crystal lattice of steel structure) accumulation increases with increased loading rates, leading to more dislocation obstacles, that in turn causes increase in yield and ultimate stresses. However, due to having finer microstructure and greater resistance to dislocation, the increase in dislocations accumulations in high-strength steel material with increased loading rate is less than that of normal-strength steel material, thereby less variation in yield and ultimate stresses of HSS compared to NSS materials.



(a)



(b)

Figure 4. Variations of dynamic increase factor vs. strain rate for (a) yield strength (f_y), and (b) ultimate strength (f_u)

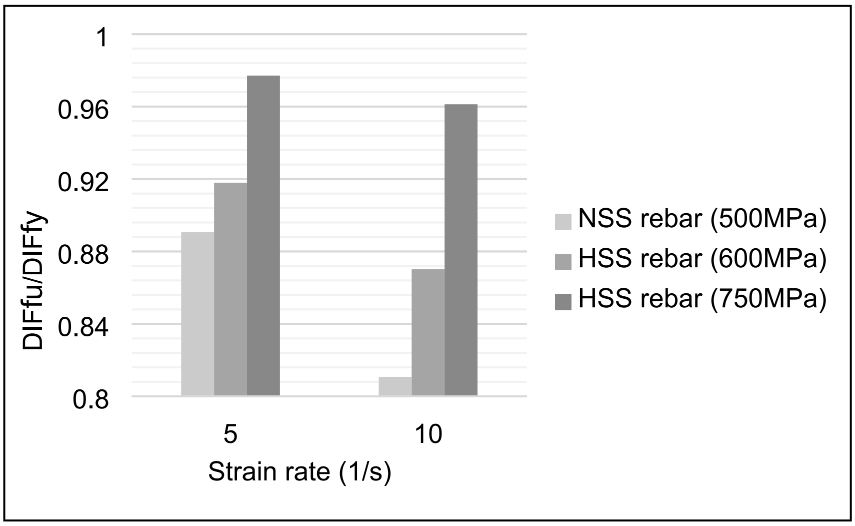
4.2.2 Ductility

The variation of dynamic increase factor of f_u/f_y ratio with respect to the strain rate and grade of steel reinforcing bars has been shown in Fig. 5. It is seen for all steel grades, the f_u/f_y ratio reduces when strain rate increases. However, the magnitude of this reduction in HSS rebars is less than that of NSS rebar. In other words, 500MPa rebars exhibit the highest reduction in f_u/f_y ratio under higher strain rate loading. Under the highest strain rate considered in this study (i.e. strain rate of 10 1/s), the f_u/f_y ratios for 500MPa, 600MPa and 750MPa rebars are, respectively, 1.08, 1.14 and 1.05. This means for the strain rate of up to 10 1/s, the f_u/f_y ratio for all steel grades of 500MPa, 600MPa and 750MPa is more than 1.04, satisfying the aforementioned requirements given by AS 4671 (8) for normal ductile rebars.

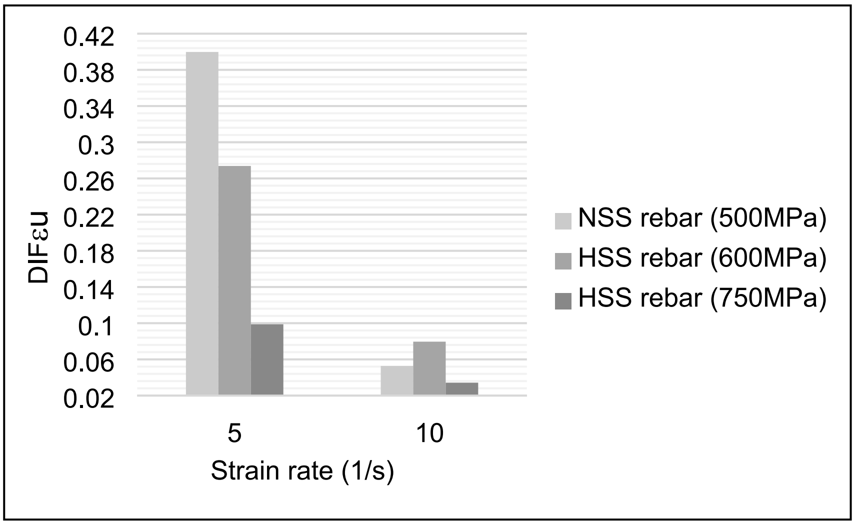
Uniform strain (ε_u) is another parameter associated with ductility of steel. Fig. 5b shows the $DIF_{\varepsilon u}$ values of uniform strain is less than one for all steel grades, indicating the fact that the ductility of steel reinforcing bar reduces dramatically when the strain rate increases. For the strain rate of 5 1/s, this reduction in uniform strain increases when the nominal yield strength of steel reinforcing bar increases. Same scenario occurs at strain rate of 10 1/s with the exception of 600MPa rebar, suggesting further experimental investigation is needed to clarify this observation.

It is worth mentioning that in accordance with AS4671 [8], the minimum uniform elongation (ε_u) of Class N 500MPa and 600MPa ductile rebars should be 5% and that of 700MPa should be 4%. The experimental tests included in this study demonstrated only uniform elongation of HSS rebars under quasi-static loading satisfy the AS4671 requirements. In other words, by increasing the strain rate to 5 and 10 1/s, the HSS rebars may no longer be classified as normal ductility rebars. This should be considered by structural engineers during design and/or evaluation of new/existing concrete structures subjected to impact loading.

To explain the reduction in ductility with increase in strain rate, one should consider that the ductile fracture mechanism of steel under uniaxial tensile loading proceeds in three stages including nucleation, growth, and coalescence of microvoids. Microvoids emerge and grow during plastic flow in places of high local plastic deformation. With an increase in strain, adjacent microvoids link together and coalesce until rupture occurs, thus resulting in a dimple mode fracture. These equiaxed dimples are spherical depressions a few micrometres in diameter that have coalesced normal to the loading axis. The size and shape of the dimple depends on the type of loading and extent of microvoid development. The brittle fracture mechanism of body-centred cubic metals, such as steel, is referred to as cleavage, which occurs when crystals cleave along crystallographic planes (9). Cleavage results in cases of high rates of deformation (10) considered in this study, leading to reduction in uniform strain and ductility. In other words, steels with higher values of uniform strain exhibit larger, deeper, and more uniform dimples with less cleavages, reminiscent of ductile behaviour. Nevertheless, a further detailed microstructure examination is needed to confirm this observation.



(a)



(b)

Figure 5. Variations of dynamic increase factor vs. strain rate for (a) ultimate strength to yield strength (f_u/f_y) ratio, and (b) uniform strain

5 Conclusions

Understanding changes in mechanical properties of high-strength steel rebars under high-strain rate loading is important. This paper reported the results of experimental tensile tests conducted on the coupons taken from the core of 500MPa, 600MPa and 750MPa rebars under various strain rates including 0.001, 5 and 10 1/s. The experimental results showed yield strength, ultimate stress, and uniform strain of HSS bars vary with strain rate in which the values of dynamic increase factor corresponding to yield strength and ultimate strength strain reduce with increase of strain rate or steel grade. It was also shown with the increase of strain rate the uniform strain of both NSS and HSS bars reduces substantially for which they cannot be classified as ductile bars under high strain rate loading conditions. Yet, it was exhibited the ratio of ultimate stress to yield stress satisfied the minimum value prescribed by Australian Standard.

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7 References

1. Yang, C, Chou, YC, Hung CC. “Seismic behavior of full-scale wall piers with high-strength steel reinforcement”. Engineering Structures, 2022; 256:114068.
2. Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, Farmington Hills, MI, 2019.
3. AS3600:2018 – Concrete structures. Standard Australia, 2018.
4. Cadoni, E, Forni, D. “Strain rate effects on reinforcing steels in tension”, The European Physical Journal Conferences, 2015, 94:01004.
5. Lin, F, Dong, Y, Kuang X. Lu, L. “Strain rate behavior in tension of reinforcing steels”, Materials Science, 2016, 9(12): 1-10.
6. Malvar, LJ. “Review of static and dynamic properties of steel reinforcing bars”, ACI Materials Journal, 1998, 95 (5), 609-616.
7. Cadoni, E, Forni, D. “Strain-rate effects on S690QL high strength steel under tensile loading”, Journal of Constructional Steel Research, 2020, 175: 2-11.
8. AS/NSZ 4671– Steel for the reinforcement of concrete. Standard Australia, 2019.
9. Mirmomeni, M, Heidarpour, A, Zhao, XL, Hutchinson, CR, Packer, JA, Wu, C. “Fracture behaviour and microstructural evolution of structural mild steel under the multi-hazard loading of high-strain-rate load followed by elevated temperature”, Construction and Building Materials, 2016, 122: 760-771.
10. Anderson, T L. “Fracture mechanics: fundamentals and applications”: CRC press, 2005.