INVESTIGATION ON PROPERTIES OF STRUCTURAL STEELS DEFORMED AT DYNAMIC CONDITIONS

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Abstract

Results of dynamic tensile tests performed for three grades of carbon structural steel are presented in the paper. The selected steels are typically used for making elements of the road sign support structures. The tests were performed on a flywheel machine that allowed to achieve strain rates corresponding to those obtained during vehicle collisions against fixed objects. Although expected positive stress sensitivity to strain rate was confirmed for all steels, two carbon steels exhibited significantly lower UTS values in tests performed at the highest strain rate (ca. to 1400 s^{-1}) due to their limited formability in such conditions. Fractographic analysis revealed ductile and mixed ductile - brittle character of fractures.

Keywords: Strain rate, dynamic tensile test, structural steel

1. INTRODUCTION

Breakaway road sign supports are the structures designed to fail when impacted by a vehicle instead of absorbing the impact energy. This solution is considered to be the most effective way to minimize the negative effects of a collision on vehicle occupants [1]. In order to achieve the intended crash behaviour of the breakaway road sign support, a proper connection of the vertical column structure with the footing is required (**Figure 1**). The structure must be strong enough to resist stress resulting from its dead weight, wind force, snow weight etc. However it should intensionally break in the right way upon vehicle impact. To ensure this - bolts playing role as safety connectors as well as rods have to be properly selected.

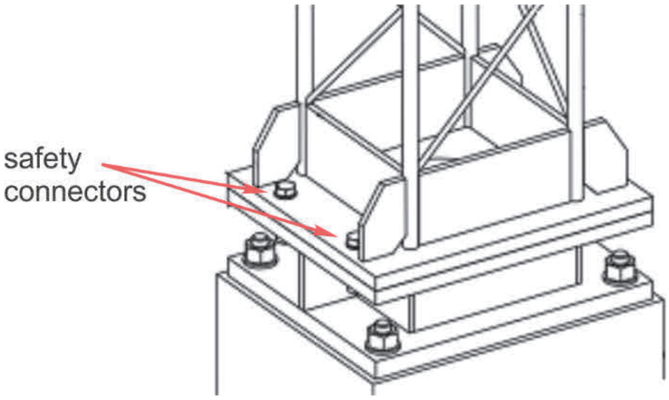

Figure 1 One of the solutions of breakaway road sign supports with bolted connections [2]

There are steels specifically developed to absorb energy by sthrenghtening during dynamic deformation, used typically in automotive industry [3-6]. Due to new design concepts for the construction of advanced light-weight and crash resistant transportation systems it is required to develop high strength and supra-ductile steels with enhanced energy absorption that additionally allow for reduction of specific weight. In contrast to them, materials used for safety connectors or rods in the case investigated should exhibit rather small strength sensitivity to the strain rate.

In the case of deformation at high strain rates, a gradual increase in the flow stress is observed, known as a sensitivity to strain rate [7, 8]. For low strain rates, a dependence of the flow stress on the strain rate is usually linear. At higher deformation rates, the stress increases rapidly with increasing strain rate. The dependence of the flow stress on the strain rate ceases to be linear [9]. In the case of carbon steels, this dependence is variable [10, 11]. The typical exponential course of stress changes as a function of strain rate is characteristic for alloyed steels, including the AHSS group. At the same time, from the point of view of structural steel properties and their dynamic behavior, there are very few works in the field on deformation by means of a flywheel machine [10]. Therefore, the main goal of this study is to assess the effect of strain rate on deformation behaviour of three various structural steel grades: C35, C30 and S355.

2. EXPERIMENTAL PROCEDURE

Dynamic tensile tests were conducted by means of a flywheel machine (**Figure 2**). A principle of the test is based on accelerating a flywheel (having a very high moment of inertia) to a required linear velocity. When it is achieved, a fork-shaped tup (initially located within the on the flywheel) is released and, in consequence, it hits an anvil that is screwed on the end of a sample. To control the velocity and measure the impact force, the device is equipped with dedicated measurement systems.

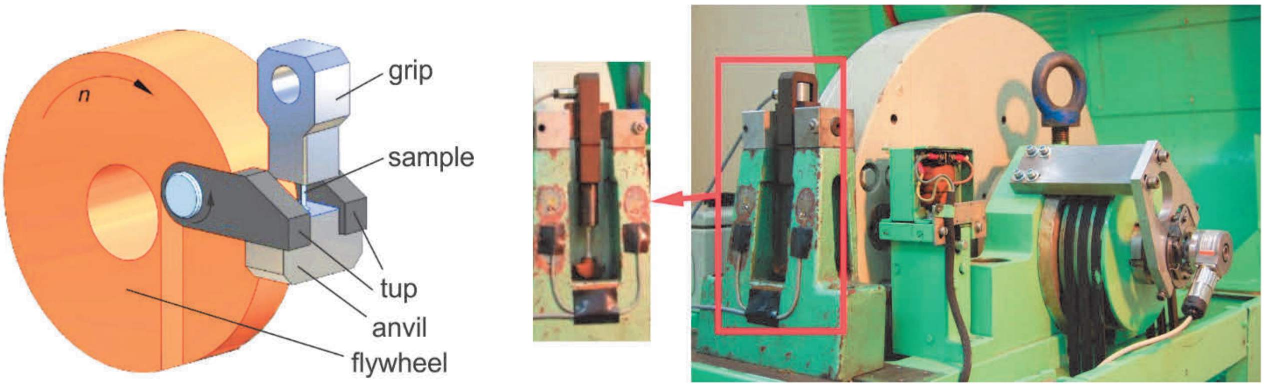

Figure 2 Tooling for tensile dynamic tests on a flywheel machine

Dynamic tensile tests were conducted at room temperature. The linear velocities of the flywheel within the range of 5 to 30 m/s were applied. In consequence, very high strain rates was achieved - ranging from 260 up to 1400 s^{-1}.

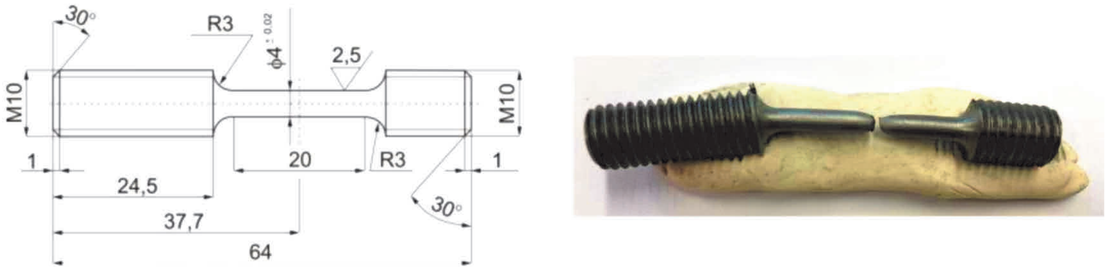

Figure 3 Geometric features of a sample and an example of the sample after the test

Scanning electron microscopy were used to find out how dynamic deformation conditions affect fracture morphology of the investigated steels. A Hitachi S-4200 scanning electron microscope equipped with the electron gun with field emission were used for investigations (magnification: 25 to 500 000, accelerating voltage: 0.5 to 30 kV, resolution 1.5 nm at 15 kV).

The materials for testing were three grades of structural carbon steel with chemical composition given in **Table 1.** From all steel these grades there are produced the bolts, playing role as safety connectors in the breakaway road sign supports construction.

Table 1 Chemical composition and nominal properties of tested steels (wt. %)

Grade	C	Mn	S, P	Cr + Mo + Ni	Mo	Cr	Ni	Si	Al	UTS (MPa)	YS (MPa)	A_5 (%)
C30	0.27-0.34	0.5-0.8	S≤0.035 P≤0.035	0.65	≤0.1	≤0.4	≤0.4	≤0.4	-	480	250	21
C35	0.27-0.39	0.5-0.8	S≤0.035 P≤0.035	0.65	≤0.1	≤0.4	≤0.4	≤0.4	-	520	290	19
S355	0.38	1.3-1.5	S≤0.035 P≤0.035	-	-	≤0.3	≤0.3	0.2-0.5	0.02	490-630	355	-

3. RESULTS AND DISCUSSION

The selected courses of force recorded during dynamic tensile tests are presented in **Figures 4, 5** and **6**. Values of the ultimate tensile strength obtained at various strain rates by investigated steels are collectively shown in **Figure 7**. Moreover, the UTS values obtained during static tensile tests for the tested steels are introduced for comparison purposes.

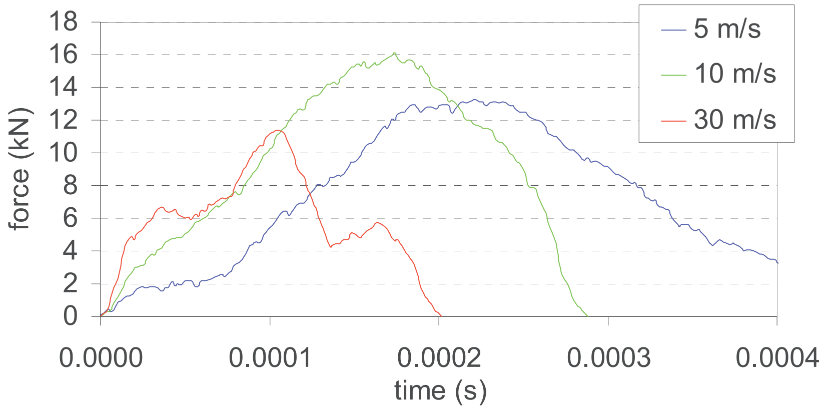

Figure 4 Force vs. time relations for C35 steel

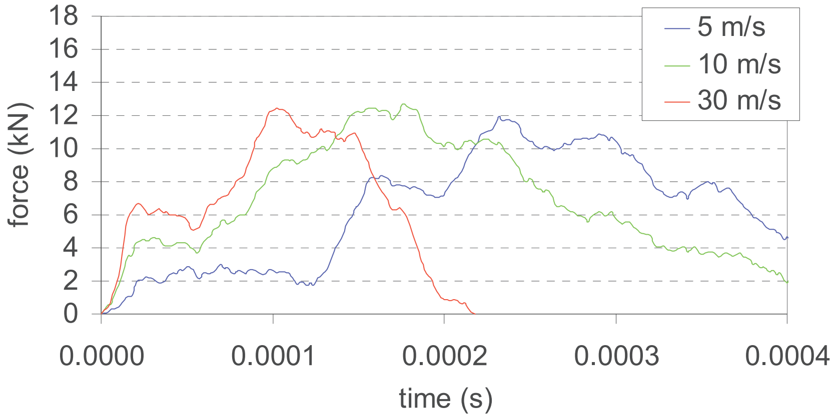

Figure 5 Force vs. time relations for C30 steel

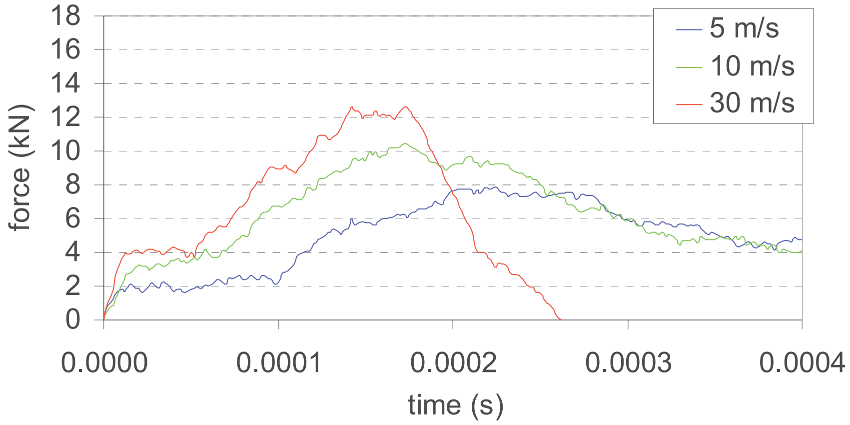

Figure 6 Force vs. time relations for S355 steel

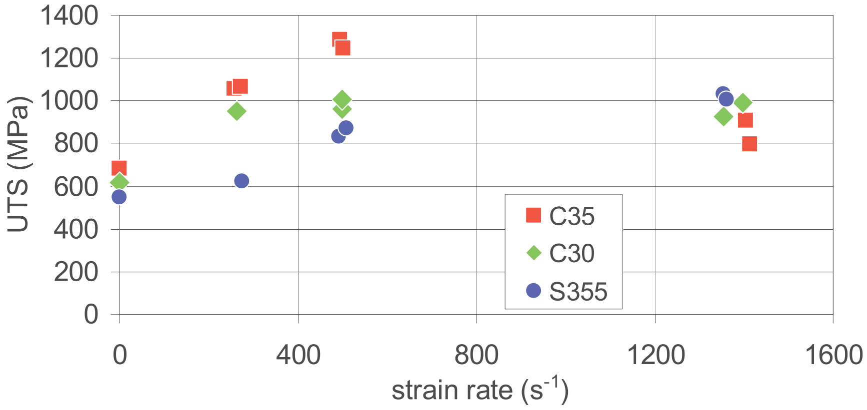

Figure 7 Ultimate tensile strength obtained at various strain rates by investigated steels

The results obtained indicate that all investigated steels for strain rates of up to 500 s^{-1} exhibit the expected behaviour - the higher the strain rate, the greater stresses are required to deform and break these materials. As in static conditions, the C35 steel is the strongest one and the S355 steel is the weakest.

However, at the highest testing strain rate (ca. 1400 s^{-1} - corresponding to the linear velocity of 30 m/s) both C30 and C35 steels exhibit significantly lower UTS values, which are even lower than ultimate tensile strength of the S355 steel which in fact follows the rule mentioned above (positive strength sensitivity to strain rate). This is probably due to relatively small value of strain to fracture of both steels in these conditions. Such deformation behaviour can be utilized in the case of selecting materials for safety connectors in breakaway road sign structures.

Selected fractographic results are presented in **Figures 8** and **9**. The fracture analysis of samples deformed with the linear velocity of about 10 m/s revealed well-defined fibrous, dimpled fractures with the occurrence of craters. Such dimple rupture due to the microvoids coalescence is the principal failure mode of ductile materials under high loads. The advantage of fine fibrous, dimpled fracture with the highest numbers of craters is observed in S355 steel (**Figure 8** S355).

A slightly different, fibrous but partially transcrystalline brittle fracture appearance is noted for both C35 and C30 steels tested with the linear velocity of 30 m/s. There are some areas with no typical crater structure that indicates the domination of a ductile fracture (**Figure 9** C35, C30). In the case of S355 steel the prevalence of fibrous fracture with dimples is revealed and transcrystalline fracture surfaces are not observed (**Figure 9** S355).

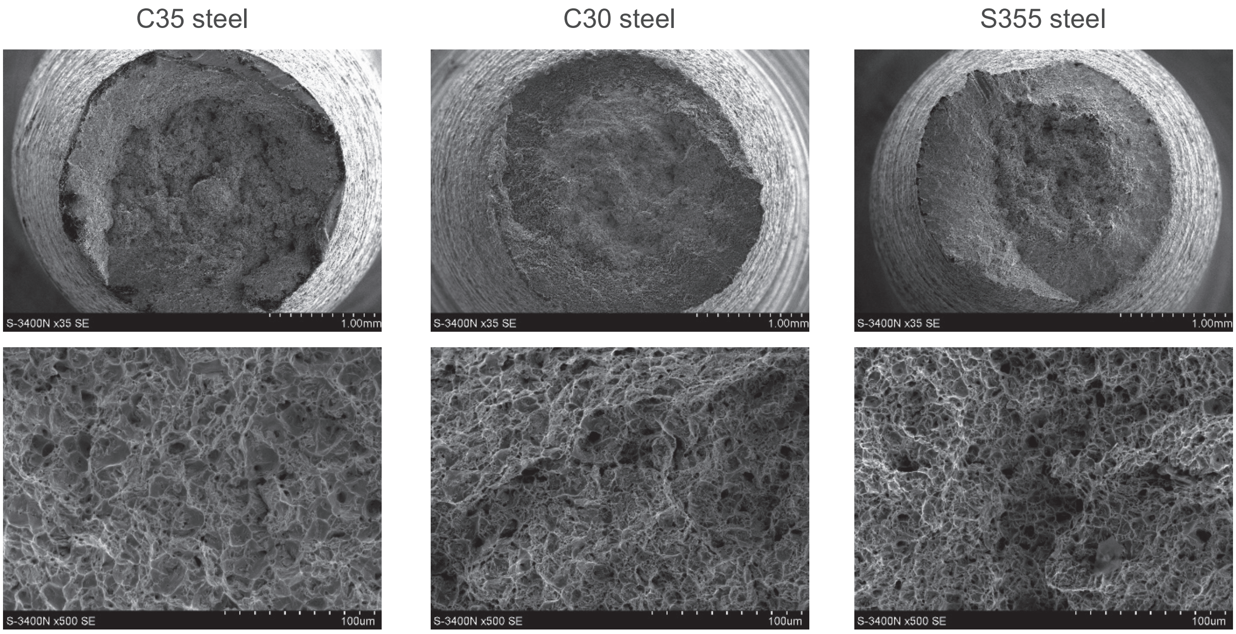
C35 steel C30 steel S355 steel

Figure 8 Fracture surfaces of samples after the tests performed with the linear velocity of 10 m/s (strain rate of ca. 500 s^{-1})

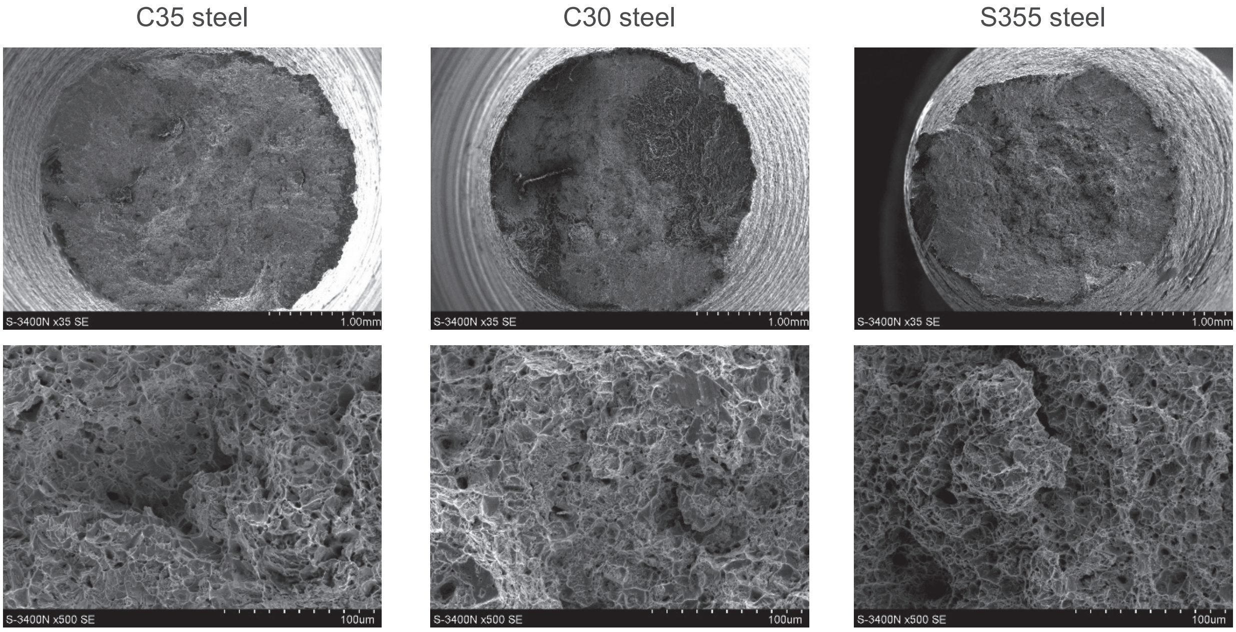
C35 steel C30 steel S355 steel

Figure 9 Fracture surfaces of samples after the tests performed with the linear velocity of 30 m/s (strain rate of ca. 1400 s^{-1})

4. CONCLUSION

- Test results obtained indicate that for strain rates of up to 500 s^{-1} all investigated steels exibit similar, positive flow stress sensitivity to strain rate - the higher it is, the greater stresses are required to deform and break these materials.
- For two investigated carbon steels: C35 and C30, significantly lower maximal forces were achieved during tests performed at the highest strain rates - such behaviour can be beneficial in applications mentioned in the introduction.

- The fracture analysis indicates that after dynamic deformation investigated steels exhibit typical, moderately ductile fracture appearance.
- For both C35 and C30 steels, fibrous and partially transcrystalline brittle fracture surfaces were observed after dynamic deformation with the highest strain rate.

ACKNOWLEDGEMENTS

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