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Reinforcement bar and reinforcement bar splicing systems under impact loading – Experimental tests and test specification

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ABSTRACT

Reinforced concrete is a widely used material for power generation structures, where load scenarios like impact loadings need to be considered. In this context mechanical splicing systems for the connection of reinforcement bars are of specific interest and impact resistance for the splicing systems has to be verified. High speed tensile tests need to be performed on splicing systems for reinforcement bars to confirm the capability of the coupler to resist impact loading. Furthermore, the ability of the reinforcement steel to dissipate energy by ductile behaviour with pronounced plastic strains should be confirmed by these tests. During the last decades comprehensive experiences were developed at BAM performing high speed tensile tests on reinforcement bars as well as on several splicing systems. For the lack of available standards defining these tests in detail an appropriate test procedure was developed and continuously optimized during this period at BAM. The test procedure is partially based on testing principles adapted from available standards. The main intention behind this test procedure is to perform high-speed tensile tests with a specific constant strain rate generated at the specimen. Furthermore, main objective was to establish a procedure to guarantee the comparability of test results for different diameter of reinforcement as well as for different types of couplers. Besides the pure execution of the high-speed tensile tests, the test specification also declares how to evaluate the measurements and the test results. Finally, some typical results will be presented in this contribution.

INTRODUCTION

Concrete is the most widely used structural material in the world for the construction of civil structures. In most applications steel bars are used as reinforcement for the concrete structures. Especially due to transportation reasons the supply length of these reinforcement bars is limited. Therefore, reinforcement bars need to be frictional connected at large structures in numerous cases due to limitations in space. In such cases so called mechanical splices for reinforcement bars are used.

Reinforced concrete structures are in most cases designed and loaded by static loads. But some specific structures are additionally exposed to potentially dynamic loads and need to be designed for extreme load cases. Examples are safety and protective structures, especially for nuclear facilities. They are made of reinforced concrete in most cases. Relevant load scenarios for such structures are dynamic load cases like impact of airplanes or detonations, additionally to the static loadings. The affected structure should be able to resist these dynamic loads.

The related loads from the load case impact need not only to be sustained by the concrete and the reinforcement bar itself, but also especially by the mechanical splices. There are several different types of such coupler systems available and offered by different manufactures. Corresponding tests need to be executed to be able to verify the qualification of these coupler systems for the extreme impact load case.

The objective of such experimental investigations on reinforcement bar coupler systems should be the verification and documentation of (a) the ductility and ability of energy dissipation of the reinforcement bars and (b) the load bearing capacity of the coupler under impact loadings based on laboratory tests. An appropriate definition of such laboratory tests as test specification is required to regulate the execution as well as the quality of such tests. It should define the preparation, the execution and the result evaluation of these high-speed tensile tests. Furthermore, the test procedure should guarantee the comparability of tests and related results from different tests and different types of coupler systems. However, there is a lack of available appropriate international standards and regulations defining such kind of tests. Only standards for static tests on reinforcement bars, ISO 15630-1 (2010), and on coupler systems, ISO 15835-1/-2 (2009), are available.

High-speed tensile tests on coupler systems are performed for several decades at the Bundesanstalt für Materialforschung und -prüfung (BAM) in Germany, Brandes et al. (1986). An appropriate test procedure was developed and documented based on these long-time experiences, following the principles from several related national and international standards and in cooperation with industry partners. The test procedure, developed at BAM, was written and published 2021 in the form of a test specification, Thiele et al. (2021). This test specification will be introduced in this contribution together with a selection of typical test results.

TEST PROCEDURE AND SPECIFICATON

The objective of the presented test specification is to provide all relevant information required for the preparation, the execution and the evaluation of high-speed tensile tests on reinforcement bar coupler systems. This high-speed tensile test procedure was developed to mimic a manmade or unplanned extreme load due to events like explosion or collision, where the mechanical splice can be loaded to failure in a very short time span. This specification is intended to regulate the testing of mechanical splices of reinforcement bars used in reinforced concrete structures. It defines the execution of experimental high-speed tensile tests in laboratories. Aim of the high-speed tensile tests is to verify the performance of the reinforcement bar coupler system under impact loading. Thereby, the mechanical behaviour of both the coupler and the bar as well as that of the connection between bar and coupler is investigated. The specification responds to the following topics:

- Specimen description and preparation
- Test facility and test setup
- Testing program and test procedure
- Evaluation and documentation of test results

Basis for the specification are long-time experiences at BAM with the execution of high-speed tensile tests on reinforcement bar coupler systems for industry customers. In addition, while developing both the test procedure and the specification, technical principles from available national standards, BS 4449 (2005) and ETC-C Part 2 (2012), and international standards, ISO 15630-1 (2010) and ISO 15835-1/-2 (2009) and ISO 6892-1 (2019), were taken into account at the related topics. The most relevant topics and test parameters will be presented in the following sections.

Test specimen

For these tests complete and representative assemblies of reinforcement bars and coupler shall be used. The reinforcement bars and the coupler shall be the same as in the application on site. It is preferred to use assembled specimen taken randomly from a series of samples which were prepared on construction site. All relevant information concerning the material, the geometry and the designation need to be known.

Figure 1. Exemplary reinforcement bar of 32 mm with mechanical splicing system (e.g. Dextra GRIPTEC Standard Splice G32).

The specimen are a connection of two reinforcement bars using a coupler system. An example of such connection is shown in Figure 1. The coupler shall be located at the middle of the specimen. The total length of the specimen is depending on the geometry of the test facility. But the free length L_0 is subjected to minimum requirements as given in Equation 1.

$$L_{0,min} = L_c + 400 + 4 \cdot (Max[1D; 20] + Max[2D;50]) \text{ [mm]} \quad (1)$$

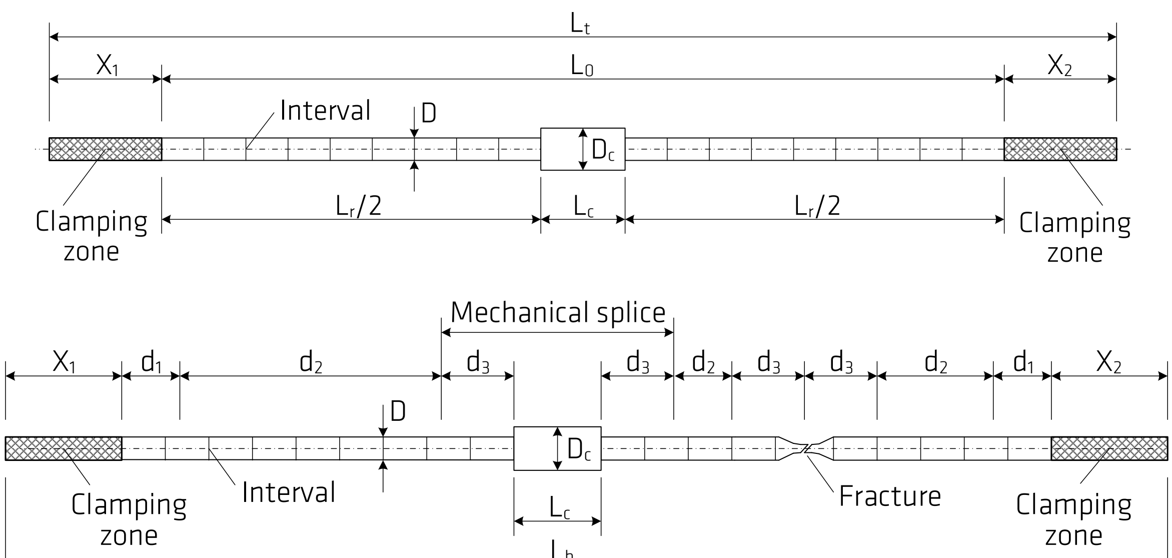

Figure 2. Geometry of specimen with coupler before and after testing with dimensions and distances (Thiele et al. (2021)).

For the measurement of the elongation of the specimen the manual method according to ISO 6892-1 (2019) is recommended. The specimen shall be engraved by scratches in regular intervals prior to the test in order to be able to measure the percentage of non-proportional elongation after failure between the scratches. Aim of the definition of a minimum free length L_0 is to assure the availability of a suitable free length of the bar for measuring the elongation outside the areas influenced by fracture and clamping. A schematic illustration of a specimen with coupler before and after the test including the definition of dimensions and various distances is given in Figure 2.

Test facility and test set up

For the high-speed tensile tests an impact test facility needs to be provided, able to apply the necessary test velocities for achieving the required strain rates. The load frame should have a very high stiffness related to the applied force. The test facility should have an appropriate high force capacity and moreover needs be able to reach an appropriate test velocity which shall be controlled to be constant during the test. The required test velocity is dependent on the length of the specimen.

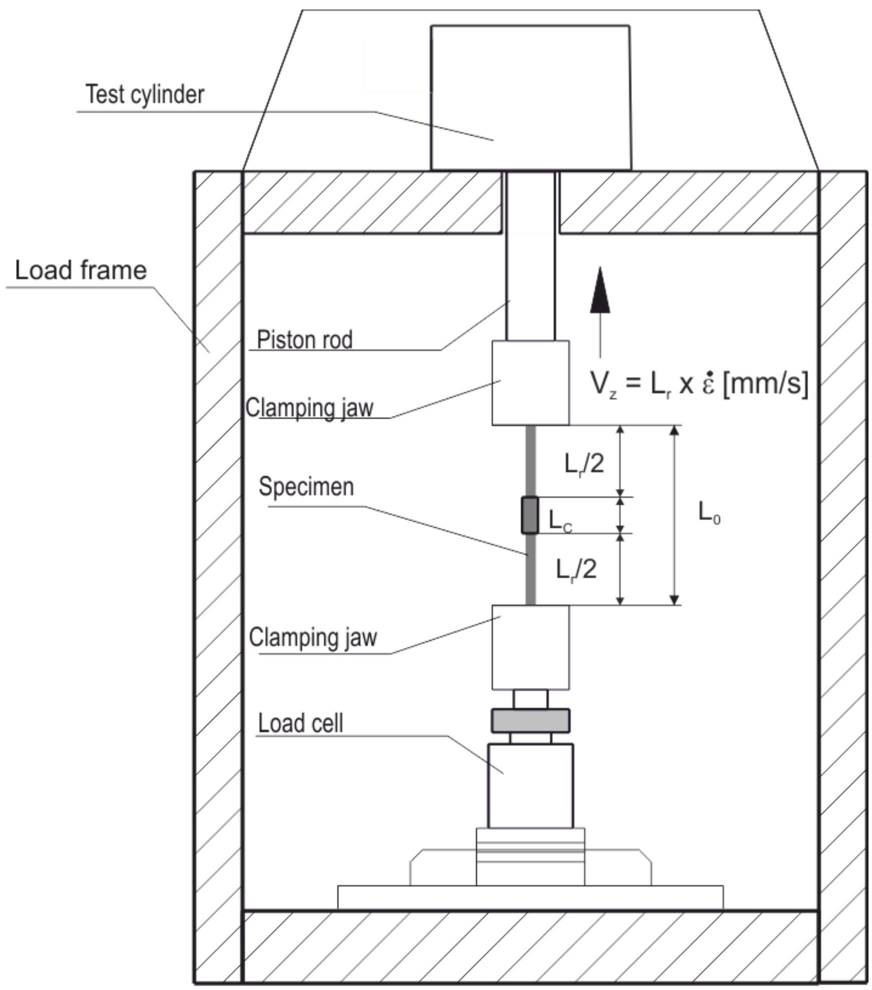

Figure 3. Schematic illustration of test arrangement for high-speed tensile tests (Thiele et al. (2021)).

Figure 3 illustrates a corresponding test arrangement for high-speed tensile tests including a load cell on the fixed part of the clamping system. To ensure comparability to other tests a calibration of the test facility of class 1 according to ISO 7500-1 is required. Caused by the high test velocities a data acquisition system for the force and displacement is needed, able to provide a sampling rate of at least 5 kHz during the experiment.

Testing procedure

The test campaign of a single type of coupler is consisting of static and dynamic tests on reference bars and bars with coupler system. During the high-speed tensile tests, a constant average strain rate of 1/s shall be reached. This value is corresponding to the requirement of ETC-C Part 2 (2012) for the execution of high-speed tensile tests on mechanical splices. A displacement control of the test facility is necessary to assure the constant strain rate. To define the test velocity of the test facility the length of the specimen for which the strain rate should be defined is necessary. In this context it should be considered at which parts of the specimen what kind of deformations are generated. It is assumed that elastic deformations are generated at the bar and at the coupler during the test. Although the elastic region is only exceeded at the reinforcement bars and plastic deformations are generated there. Those plastic deformation at the reinforcement bars are dominating the deformations during the test. Results from many high-speed tensile tests on reinforcement coupler systems at BAM have confirmed this assumption. Based on this background only the effective length (Equation 2) of the reinforcement bars needs to be used for the calculation of the test velocity (Equation 3).

$$L_r = L_0 - L_c \tag{2}$$

$$v_z = L_r \cdot \dot{\varepsilon} \tag{3}$$

Moreover, this definition guarantees the comparability of the results from different tests due to the always same strain rate of 1/s. Since numerous different types of coupler systems from different manufactures are available, a lot of different lengths of coupler are existing. Without considering the effective length of the reinforcement bar very different strain rates would be generated at the different types of couplers during the high-speed test and a comparability of the results would not be possible.

Test results and evaluation

It is mandatory that the coupler does not fail during the test and therefore the failure takes place at the reinforcement bars. In addition, the calculated test velocity and strain rate should be reached. After the test the generated elongations are measured at the specimen using the scratches. Based on these values the non-proportional elongation A_g is calculated according to ISO 15630-1 (2010) besides the calculation of the reached stress. Furthermore, the total elongation A_{gt} is calculated according to ISO 15630-1 (2010). These values will be calculated for the broken and the unbroken side of the reinforcement bar. The reached total elongation A_{gt} should be greater than 5 % in line with ETC-C Part 2 (2012) and greater than 7.5 % in line with BS 4449 (2005) at the broken side.

In addition to the values of elongation it is required to evaluate the failure mode and the location of fracture. The failure mode shall be ductile with pronounced plastic deformations and necking at the fracture zone. Furthermore, the fracture location shall fulfil corresponding requirements related to minimum distances to the coupler and the clamping as well as a minimum length for the deformation measurement. These values are defined according to ISO 15630-1 (2010) and ISO 15835-2 (2009) and are given in Table 1 as well as illustrated in Figure 2.

Table 1: Required distances for specimen with mechanical splice (Thiele et al. (2021)).

Type of distance	Requirement
d_1	≥ Max (20 mm or 1xD)
d_2	≥ 90 mm (preferably ≥ 100 mm)
d_3	≥ Max (50 mm or 2xD)

TEST FACILITY AND RESULTS

Specimen

For the execution of high-speed tensile tests at BAM specimen are required with a total length of L_t = 1250 mm and a coupler located in the middle of the specimen. Such specimen are shown in Figure 4 as a reference bar and a bar with coupler system for a bar diameter of 32 mm. Specimen with a bar diameter up to 40 mm can be tested. For the measurement of the elongation engraved scratches with a regular interval of 30 mm are applied to the specimen by a test bar dividing machine before the tests.

Figure 4. Exemplary reference bar of 32 mm and 32 mm reinforcement bar with coupler before high-speed tensile tests (e.g. Dextra GRIPTEC Standard Splice G32).

Test facility

For the execution of the high-speed tensile tests, a servo-hydraulic Impact Testing Machine is available at BAM which was specifically developed for test of structural members under impact load (see Figure 5). It provides of a very high stiff load frame and can apply a maximal force of ± 1,000 kN and a maximum displacement of 250 mm. The test facility is able to reach test velocities up to 4.5 m/s. The solid load frame ensures a trouble-free closed loop control and a transfer of the control variable to the specimen. It is equipped with a hydraulic clamping system and a load cell located at the lower clamping device which both have a capacity of 1,000 kN.

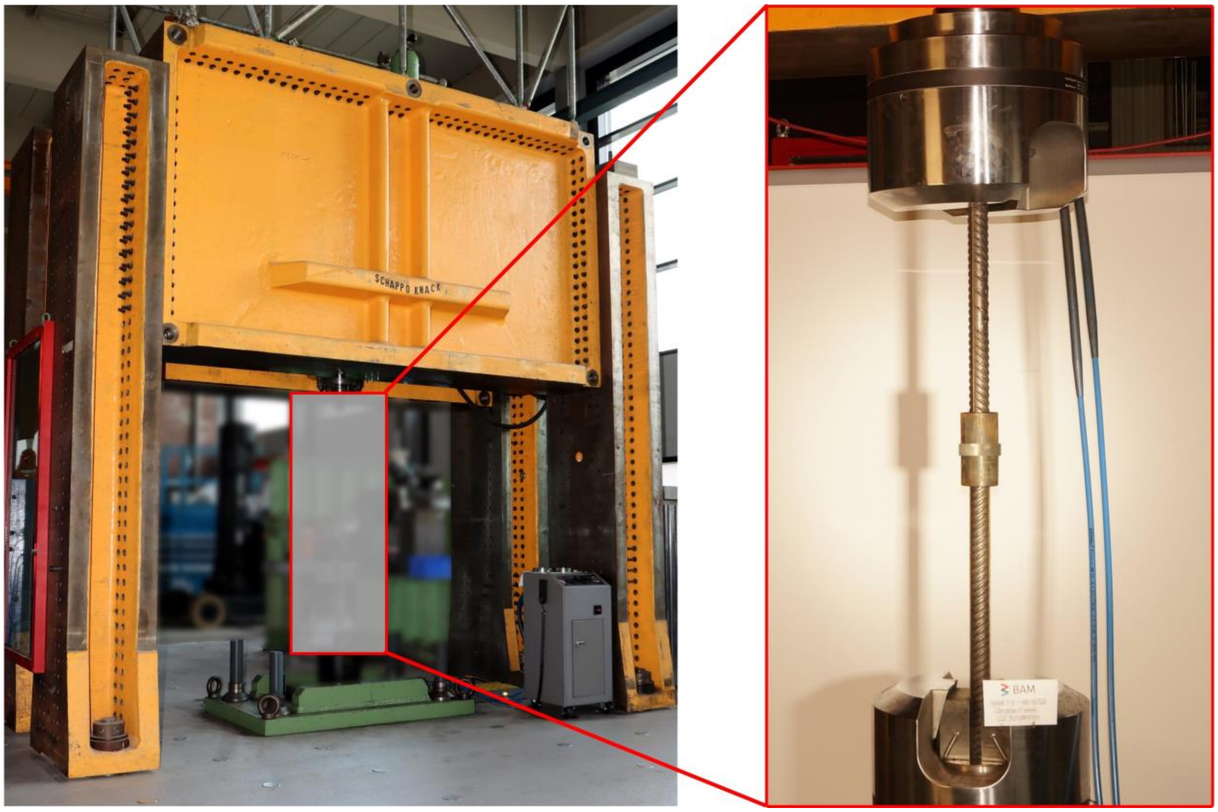

Figure 5. Test setup for high-speed tensile tests with servo hydraulic Impact Test Machine at BAM with 1,000 kN clamping system and 1,000 kN force capacity.

An average constant strain rate of 1/s should be reached at the effective length of the reinforcement bars as already described in the section Testing Procedure. Therefore, the velocity of the piston rod is calculated according to Equation 3 based on the effective length of the reinforcement bars. For a reference bar without coupler the effective length L_r is about 1,000 mm and the corresponding test velocity is 1,000 mm/s. The execution of the test is done in displacement control up to the failure of the specimen.

Results

In this section some exemplary results from three different high-speed tensile tests on specimen with reinforcements bars of 32 mm diameter are presented.

- Reference bar without coupler: $L_r = L_0 = 1{,}000$ mm; $v_z = 1{,}000$ mm/s
- Specimen with coupler: $L_r = 545$ mm; L_0=1,000 mm $v_z = 1{,}000$ mm/s
- Specimen with coupler: $L_r = 545$ mm; L_0=1,000 mm $v_z = 545$ mm/s

Both specimen with coupler were tested with different calculated test velocities v_z. The results of all three high-speed tensile tests are given in Figure 6 and Figure 7. The results of these tests illustrate very clear the influence of the reference length used for the calculation of the test velocity on the resulting strains as well as on the resulting strain rates.

Figure 6 shows the stress-strain relationship for the three tests which was calculated based on the displacement of the piston rod and the measured force from the load cell. Clearly visible are the elastic zone, the yielding zone and the zone of strain hardening in all three tests.

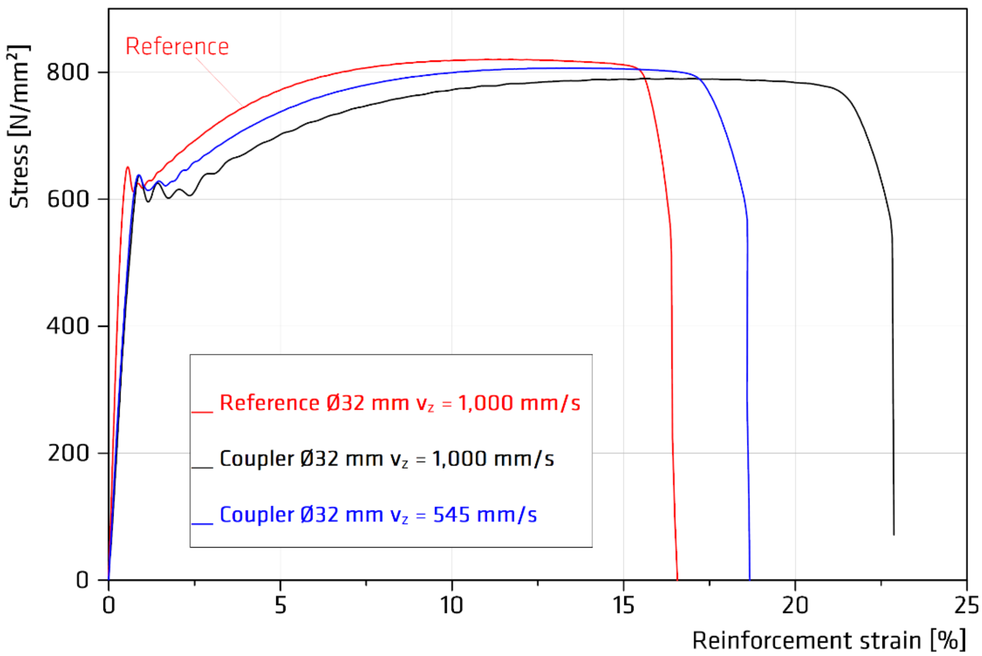

Figure 6. Comparison of stress-strain-relationship of a 32 mm reference bar and a coupler system at strain rate 1/s at the rebar together with a coupler system tested at a total test velocity of 1,000 mm/s.

Figure 7 shows the corresponding development of the average strain rates in the reinforcement bars over the time. After the start phase of acceleration all three tests reach a relative constant strain rate kept during the longest part of test up to the failure of the specimen.

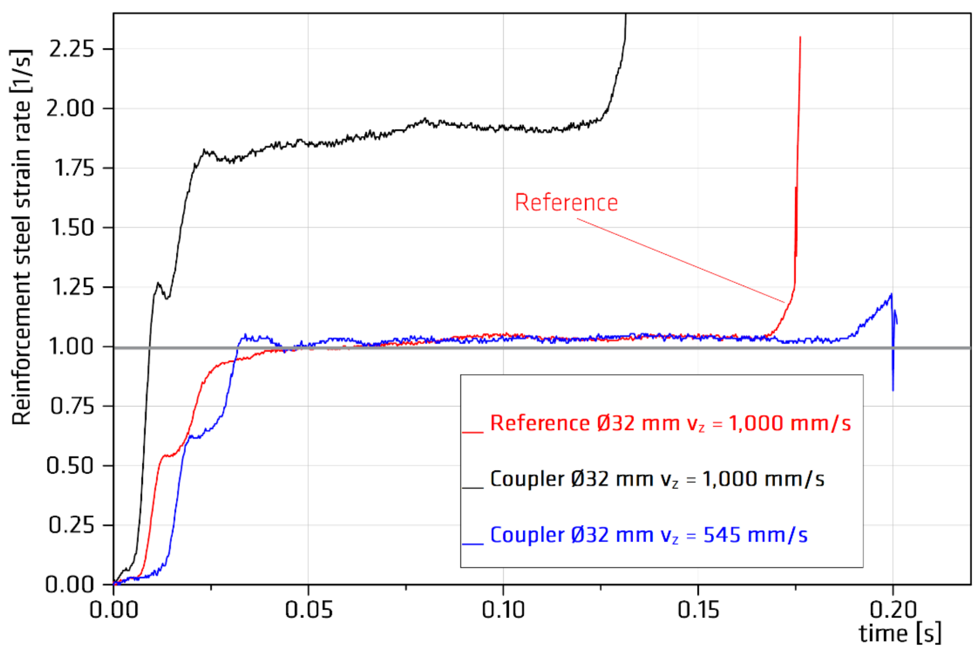

Figure 7. Comparison of strain rate time development of a 32 mm reference bar and a coupler system at strain rate 1/s at the rebar together with a coupler system tested at a total test velocity of 1,000 mm/s.

Furthermore, the results point out that the required strain rate of 1/s can be reached at the reinforcement bars by using the effective length L_r of the reinforcement bars even at different specimen geometries. In contrast, using the length L_0 between the clamping for the calculation of the test velocity leads to significant deviating high strain rates at the reinforcement bars, depending on the length of the coupler. That shows that the resulting strain rate in high-speed tensile tests is strongly dependent on the geometry of the specimen, specifically on the length of the coupler. Moreover, higher strain rates are causing higher values of plastic strains at the end of the test, as shown in Figure 6.

These results are illustrating that it is strongly recommended to calculate the test velocity for these kinds of high-speed tensile tests based on the effective length L_r of the reinforcement bars and not on the length L_0 between the clamping. Only this procedure ensures comparable stain rates and therefore comparable test results for testing of different coupler types or geometries.

Figure 8. Fracture surfaces of a 40 mm rebar after high-speed tensile test with ductile failure (left) and brittle failure (right).

Besides that, it is also required to evaluate the mode of failure of the tested specimen. The failure mode should be of ductile fracture with pronounced plastic deformations. Figure 8 is showing the fracture surfaces from two reinforcement bars with 40 mm diameter. The left one exhibits a very ductile fracture behaviour while the right one exhibits a very brittle behaviour with little plastic deformations.

CONCLUSION

This contribution presents a test procedure as well as the related test specification describing the preparation, execution and evaluation of high-speed tensile tests on reinforcement bar coupler systems in detail. This was necessary for the lack of available international standards, dealing with such kind of tests. The presented test procedure aims on an average constant strain rate of 1/s which will be reached by a test velocity calculated based on the effective length L_r of the reinforcement bars. In this way it can be assured that comparable results are generated from tests of different coupler systems and furthermore of related reference bars. The presented test results have confirmed that a relatively constant and comparable average strain rate was reached during the longest part of the executed high-speed tensile tests even at different geometries of the specimen. Moreover, the results are confirming the fact that higher strain rates result in higher plastic strains. Therefore, the presented test specification enables the testing, the evaluation and the comparison of the bearing capacity of reinforcement bar coupler systems under impact loadings.

REFERENCES

Brandes, K., Limberger, E., Herter, J. and Berner, K. (1986). „Zugversuche an Betonstahl mit erhöhter Dehngeschwindigkeit- Reinforcing Steel Tension Tests with high strain rates," (in German), Forschungsbericht 129 der BAM, ISBN 3-88 314-569-6.

Thiele, M., Makris, R. and Baeßler, M. (2021). "Specification for high-speed tensile tests in reinforcement bar coupler systems", Bundesanstalf für Materialforschung und -prüfung (BAM), Germany

ISO 7500-1: "Metallic materials – Verification of static uniaxial testing machines"

ISO 6892-1: (2019). "Metallic materials – Tensile testing – Prat 1: Method of test at room temperature"

ISO 15630-1: (2010). "Steel for the reinforcement and prestressing of concrete- Test methods, Part 1: Reinforcing bars, wire rod and wire"

ISO 15835-1: (2009E). "Steels for the reinforcement of concrete- Reinforcement couplers for mechanical splices of bars", Part 1: Requirements

ISO 15835-2: (2009E). "Steels for the reinforcement of concrete- Reinforcement couplers for mechanical splices of bars", Part 2: Test methods

British Standard BS 4449: (2005). "Steel for the reinforcement of concrete-Weldable reinforcing steel-Bar, coil and decoiled product-Specification"

ETC-C EPR (2012) Technical Code for Civil Works, 2012 Edition, AFCEN