

Specification for high-speed tensile tests on reinforcement bar coupler systems

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1. Introduction

This document presents the specification for the execution and evaluation of high-speed tensile tests on reinforcement bar coupler systems. This specification was developed at BAM - Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing, Germany) - following test principles from related international standards.

The present document represents the latest status of the test specification. It is noted that until 2010 the test procedure was characterised on a test velocity based on L_0 . In an improved test conception and after intensive investigations in cooperation with industry partners, this procedure has been updated to consider instead a test velocity based on L_r , since this warrants more comparable and meaningful results.

2. Scope

The intention of this document is to specify all necessary requirements concerning the specimens, the tests, the execution and the evaluation of high-speed tensile tests on reinforcement bar couplers. The high-speed test is 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 for the testing of mechanical splices of reinforcement bars to be used in reinforced concrete structures. The execution of this type of tests is generally necessary when the verification of the bearing capacity of the connection under impact loading is required in addition to the verification of the static bearing capacity.

The aim of the high-speed tensile tests is the verification of the performance of reinforcement bar coupler systems 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 applied strain rate of the reinforcing bar in the high-speed tests is generally set to about 1.0 s^{-1} , which also corresponds to the values specified by ETC-C [9] and EDF [8]. The test procedure described here is based on testing principles adapted from ETC-C 2012 Edition Part 2 [9] and ISO 15630-1 [4]. The impact tests should permit the identification of the failure mode under high-speed tensile loading and help to elucidate whether the connections are capable of bearing the tensile force up to the failure of the reinforcing bar. Furthermore, these tests also provide the corresponding stress-strain relationship and the value of the non-proportional elongation in the reinforcement bar after failure. Additional static tests on non-spliced reference bars also need to be executed to formally identify the steel grade of the reinforcing bars used in the high-speed tensile test. Finally, high-speed tensile tests on reference bars are also included to verify that the reinforcing steel of all spliced specimens has been obtained from the same rod.

3. Normative references

This document refers to the following standards and documents:

- [1] Brandes, K., Limberger, E., Herter, J. und Berner, K.:
„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/November 1986.
- [2] ISO 7500-1: “Metallic materials – Verification of static uniaxial testing machines”
- [3] ISO 6892-1: 2019: “Metallic materials – Tensile testing – Part 1: Method of test at room temperature”
- [4] ISO 15630-1: 2010: “Steel for the reinforcement and prestressing of concrete- Test methods, Part 1: Reinforcing bars, wire rod and wire”
- [5] ISO 15835-1: 2009(E): “Steels for the reinforcement of concrete- Reinforcement couplers for mechanical splices of bars“, Part 1: Requirements
- [6] ISO 15835-2: 2009(E): “Steels for the reinforcement of concrete- Reinforcement couplers for mechanical splices of bars“, Part 2: Test methods
- [7] British Standard BS 4449: 2005: “Steel for the reinforcement of concrete-Weldable reinforcing steel-Bar, coil and decoiled product-Specification”
- [8] EDF, EDTGC 100239, Revision B (in French)
- [9] ETC-C EPR Technical Code for Civil Works, 2012 Edition, AFCEN

4. Terms and definitions

The following terms and definitions are used throughout this specification:

4.1. Coupler length

Actual length of the coupler including all load-transferring parts, if more than one, and including lock nuts, if any.

4.2. Length of mechanical splice

Coupler length plus two times the nominal bar diameter at both ends of the coupler

NOTE: This is an agreed convention to take account of the affected zone in an approximate way. (According to ISO 15835-1: 2009(E) [5])

4.3. Mechanical splice

Complete assembly of a coupler or an end-bearing sleeve including any additional intervening material or other components providing a splice of two reinforcing bars.

4.4. Reinforcement coupler

Coupling sleeve or threaded coupler for mechanical splices of reinforcement bars for the purpose of providing transfer of axial tension and/or compression from one bar to the other, where:

- coupling sleeve refers to a device fitting over the ends of two reinforcing bars, while
- threaded coupler is a threaded device for joining reinforcing bars with matching threads.

5. Symbols

Symbol	Unit	Designation
A_{30}	%	Percentage non-proportional elongation of a marked gauge interval on the reinforcement bar at failure
A_g	%	Percentage of non-proportional elongation at failure
A_{gt}	%	Percentage of total elongation at maximum force
A_{maxF}	%	Percentage of non-proportional elongation at maximum force
A_N	mm ²	Nominal cross-sectional area before test
D	mm	Diameter of the reinforcement bar
D_c	mm	Diameter of the coupler
d_1	mm	Distance between clamping and measurement range (d_1 must be at least equal to D , and in no case less than 20 mm)
d_2	mm	Length of measurement range (d_2 should be 100 mm or more if possible)
d_3	mm	Distance between failure and measurement range (d_3 must be at least equal to $2D$, and in no case less than 50 mm)
ε	-	Strain (either $\Delta L/L_0$ or $\Delta L/L_r$)
ε_{el}	-	Elastic part of strain
ε_{pl}	-	Plastic part of strain
ε_{tot}	-	Total strain
$\dot{\varepsilon}$	s ⁻¹	Strain rate
F	kN	Measured force
L_0	mm	Clearance measured between the clamping jaws before test
L_b	mm	Length of the specimen after test
L_c	mm	Length of the connection (coupler length)
l_{el}	mm	Elastic elongation during the experiment
l_{pl}	mm	Plastic elongation during the experiment
L_r	mm	Effective length of the reinforcement steel without coupler Reference length for the evaluation of the strain values
L_t	mm	Total length of the specimen before test
ΔL	mm	Elongation of the specimen during test
σ_{max}	N/mm ²	Maximum tension stress, (F_{max}/A_n)
σ_z	N/mm ²	Tension stress, (F/A_n)
T	s	Time
v_z	mm/s	Velocity of the piston rod (pre-set value)
$v_{z,a}$	mm/s	Velocity of the piston rod (actual value)
W_1	mm	Displacement of the piston rod
X_1, X_2	mm	Clamping length

6. Specimen

Representative materials and specimen shall be used for the tests. The reinforcement bars to be assembled for the specimen with coupler shall be the same as in the application situation on site. The reference bars shall be of the same type and batch as used for the specimen with coupler. If possible, the assembled specimen should be taken randomly from a series of samples which were prepared on construction site.

6.1. Geometry

6.1.1. Reference bars

The initial geometry of the reference bars before testing is illustrated in Figure 1 including the definition of dimensions and markings for measurement of the elongation. In Figure 2 the geometry of the reference bar after testing is illustrated including the definition of dimensions for the various distances.

The following information shall be specified for the reference bars:

- Related specification standard for reinforcement steel
- Grade of reinforcement steel
- Nominal size of the bar
- Rib geometry of the bar
- Inspection documentation or certificate

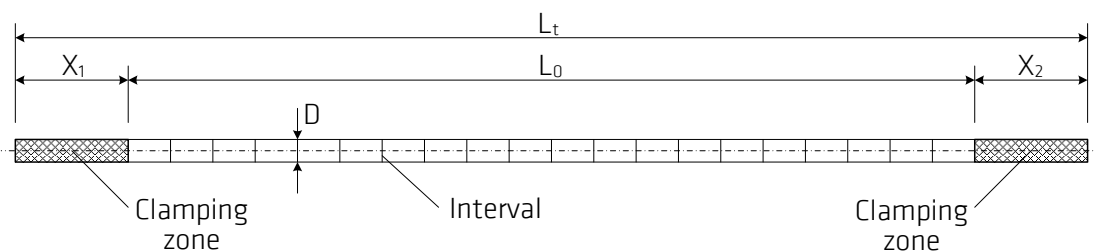


Figure 1: Geometry of reference bar before testing with definition of dimensions

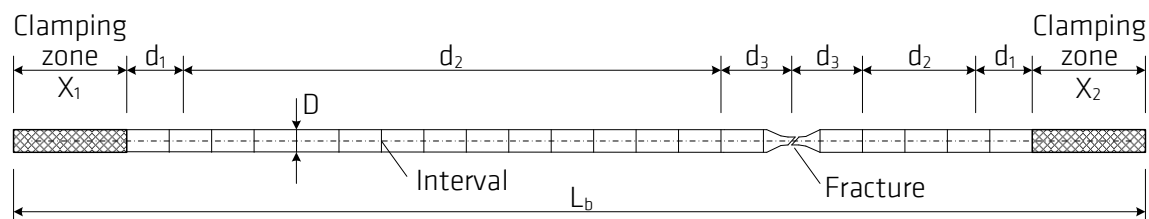


Figure 2: Geometry of reference bar after testing with definition of dimensions and distances

The following requirements for the distances must be fulfilled by the reference bars in accordance to ISO 15630-1 [4]:

Table 1: Required distances for reference bars

Type of distance	Requirement
d_1	$\geq \text{Max (20 mm or } 1 \times D)$
d_2	$\geq 90 \text{ mm (preferably } \geq 100 \text{ mm)}$
d_3	$\geq \text{Max (50 mm or } 2 \times D)$

- It is recommended that the reference bars have the same length L_t as the specimen with coupler system.
- The length of clamping zone (X_1 , X_2) shall be sufficient to avoid any slip.
- The required length for high-speed tensile test at BAM is $L_t = 1250 \text{ mm}$.

6.1.2. Rebar coupler systems

The specimens with coupler system consist of a completely assembled splicing system including any additional intervening material, which provides a splice of two reinforcement bars.

The following additional information about the splicing system must be specified:

- Manufacturer
- Name and type of coupler (product name)
- Labelling of product
- Nominal diameters or reinforcement bars for which the product is designed
- Assembly instruction for the coupler system

The geometry of the specimen before testing is illustrated in Figure 3 including the definition of dimensions and markings for measurement of the elongation. In Figure 4 the geometry of the specimen after testing is illustrated including the definitions for the various distances.

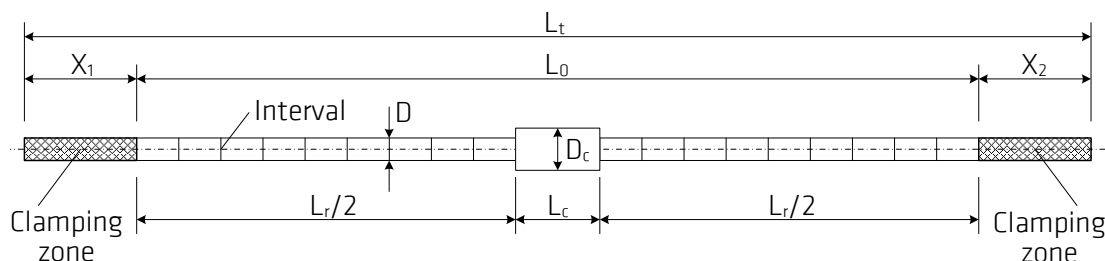


Figure 3: Geometry of specimen with coupler before testing with definition of dimensions

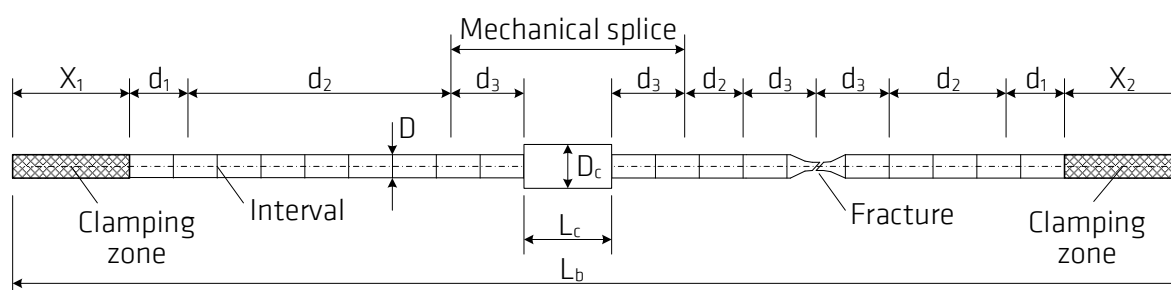


Figure 4: Geometry of specimen with coupler after testing with definition of dimensions and distances

The same requirements apply for the distances at the specimen with coupler and shall be fulfilled in accordance to ISO 15630-1 [4] as given in Table 2:

Table 2: Required distances for specimen with mechanical splice

Type of distance	Requirement
d_1	$\geq \text{Max} (20 \text{ mm or } 1 \times D)$
d_2	$\geq 90 \text{ mm (preferably } \geq 100 \text{ mm)}$
d_3	$\geq \text{Max} (50 \text{ mm or } 2 \times D)$

- The specimen shall be assembled and prepared for the test according to the assembly instructions provided by the supplier of the coupler system.
- The coupler shall be located in the middle of the specimen.
- The specimen shall have a minimum free length L_0 of:

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

- L_0 should be almost the same length in all tests for one test series.
- The length of clamping zone (X_1 , X_2) shall be sufficient to avoid any slip.
- The required total length for high-speed tensile test at BAM is $L_t = 1250 \text{ mm}$.

- In case the required distances specified in Table 2 cannot be fulfilled, this must be stated accordingly in the test report.
- In case the minimum requirement for d_2 cannot be met on the broken side, the unbroken side of the specimen can be used for an alternative evaluation. This shall be stated accordingly in the test report.
- In case the minimum length $L_{0,min}$ cannot be fulfilled, it shall be stated accordingly in the test report. In this case, it shall be ensured that at least a minimum measurement length of $d_2 \geq 90$ mm (but preferably not less than 100 mm) is available either at the broken or at least at the unbroken side.

6.2. Preparation

- Preferably the specimens should be provided already assembled by the customer according to the assembly instruction. A description of the assembly procedure must be provided.
- All relevant dimensions of the specimen and coupler shall be measured and documented.
- In case of specimens with a mechanical splice of type “Position”, the gap between the spliced parts of the coupler system shall be set in the most unfavourable condition (e.g. maximum gap).
- All specimens shall be marked by engraved characters on both face sides to ensure a clear identification of each specimen.
- In case of using the manual method (According to ISO 6892-1:2009 [3]) for measuring the non-proportional elongation A_g , all specimens shall be engraved in order to be able to measure the percentage non-proportional elongation after failure between the scratches.
- The preparation of the engraved scratches on the reinforcement bar can be done by means of a test bar dividing machine.
- A regular interval of 30 mm or a similar appropriate length shall be engraved with sufficient accuracy on the bars.

7. Test facility – Test set up

7.1. Test facility

An impact test facility capable of applying the necessary test velocity to achieve the required strain rate at the specimens shall be used for the high-speed tensile tests, as illustrated in Figure 5. Therefore, the test facility must be able to operate in displacement control.

- The load frame must have a very high stiffness related to the applied forces.
- The test facility must be equipped with a load cell and a displacement sensor.
- The test facility shall be calibrated in accordance to class 1 or higher as specified in ISO 7500-1 [2].

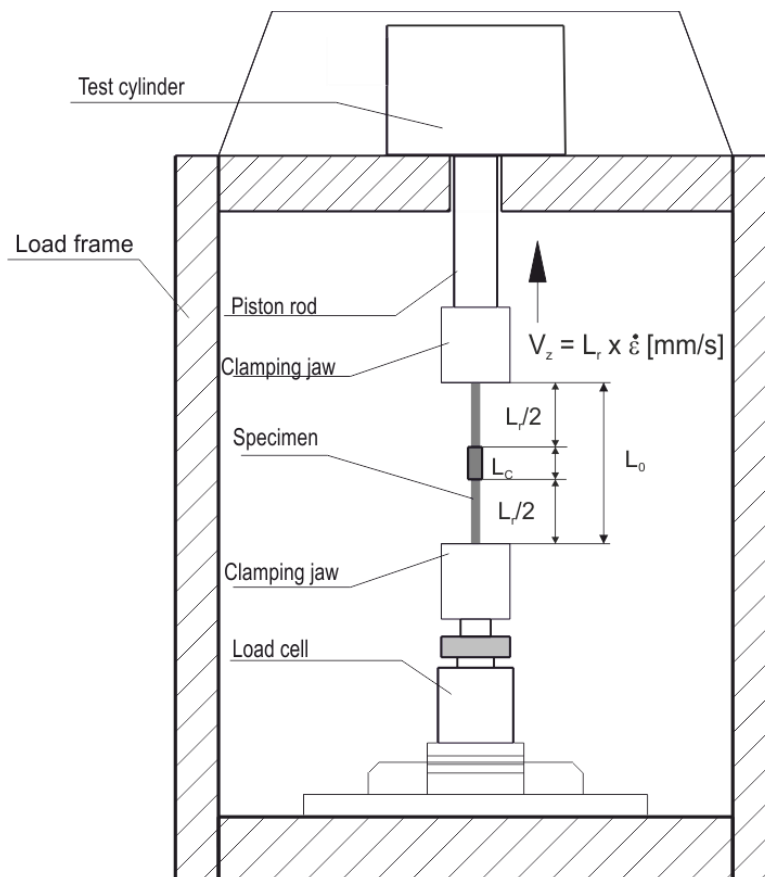


Figure 5: Schematic illustration of test arrangement for high-speed tensile tests

7.2. Measurements

The digital data acquisition system employed for the test must record both force and displacement with a sampling rate of at least 5 kHz during the experiment.

8. Background and method for high-speed tensile tests

This chapter describes the objective of the execution of high-speed tensile tests on reinforcement coupler systems. Furthermore, the background for the test method is given.

8.1. Objective of high-speed tensile tests

The objective of the high-speed tensile test is the verification of the behaviour of reinforcement coupler systems under dynamic loading (e.g. impact) as required for example by ETC-C [9] or EDF [8]. Therefore, a defined constant strain rate should be applied. The achieved average strain rate shall be as far as possible equal for all high-speed tensile tests to ensure comparable results. The main requirements are:

- **Strain rate:** A constant average strain rate of $\dot{\epsilon} = 1.0 \text{ s}^{-1}$ shall be reached.
- **Coupled tests:** In all tests of coupled specimens, the same strain rate shall be achieved.
- **Reference tests:** For high-speed reference tests the same strain rate shall be achieved as in the high-speed tensile tests of coupled specimens.
- **Comparability:** Comparable results shall be generated for the evaluation of the different test results.

8.2. Components of strain and strain rates

The following explanation illustrates the single components of strain, deformation and strain rate taking place in reinforcement bars with mechanical splices under high-speed tension loading. Thereby, the relationships between strain, deformation, strain rate and test velocity are shown.

Strains

- It is known that the material behaviour is dependent on the strain rate of the material. In general, higher strain rates lead to higher stresses and larger deformations at failure [1]. Therefore, the effective strain rate achieved during the test is of high relevance for the interpretation of the test results.
- Specimen without mechanical splice, like reference bars (pure reinforcement steel), have the same geometry and material properties over the specimen length. Therefore, the strain rate will be nearly constant over the specimen length and over the duration of the test.
- Specimen with mechanical splice consists of two different parts, the bar and the coupler. Based on that, the strain rate is typically not constant over the specimen length and over the duration of the test.
- Usually the diameter of the coupler (D_c) is larger than that of the reinforcement bar (D). Additionally, the material grade of the coupler is typically higher than the grade of the reinforcement bar.

- The result for the strain components in reinforcement bars with mechanical splice is shown in Figure 6 and Figure 7 and can be described as follows:
 - Most of the strain and deformation will occur at the reinforcement bar which has weaker material characteristics. The bar will generally transit from the elastic region (Phase I) to the plastic region (Phase II), as illustrated in Figure 6. Large plastic deformation will be generated in the bar until its rupture.
 - The material of the coupler remains mostly in the elastic region (Phase I). Therefore, the coupler will only marginally contribute to the overall plastic deformations.
 - Plastic strains within the bar are the dominant strains developing during the high-speed tensile test. They represent the largest part of the strains. The elastic region is very small compared to the plastic region (see Figure 6)
- **Mechanical splice for diameter transition:** A special case are coupler for the connection of reinforcement bars with different diameters. Plastic strains of Phase II will be generated there typically only in the reinforcement bar with smaller diameter, in case the material grades of both rebars do not differ much.
- Results from a large number of high-speed tensile tests on reinforcement coupler systems have confirmed the assumption that almost no plastic strains occur at the coupler.

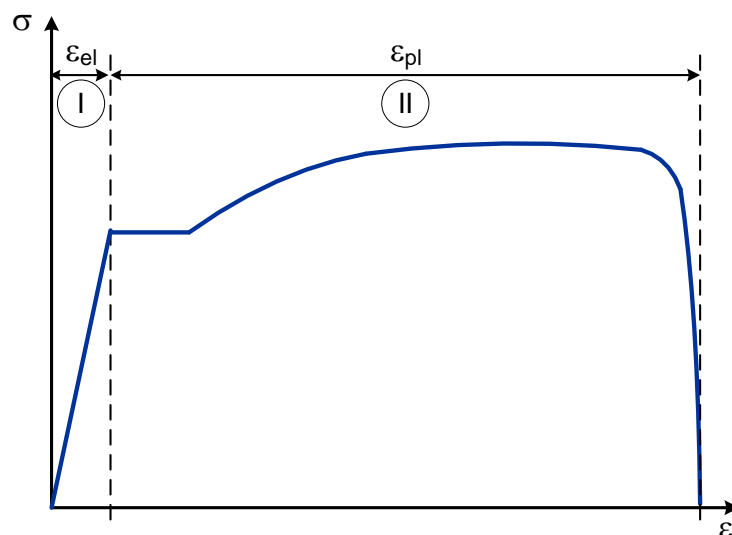


Figure 6: Schematic stress-strain-relationship for a high-speed tension test with the region of elastic strains (Phase I) and region of plastic strains (Phase II)

- Following statements can be done for the strain components in high-speed tensile tests on reinforcement coupler systems:

$$\varepsilon_{\text{tot}} = \varepsilon_{\text{el}} + \varepsilon_{\text{pl}}$$

Phase I: ε_{el}

Phase II: ε_{pl}

$$\varepsilon_{\text{pl}} \gg \varepsilon_{\text{el}}$$

$$\varepsilon_{\text{pl}}^{\text{Coup}} \sim 0$$

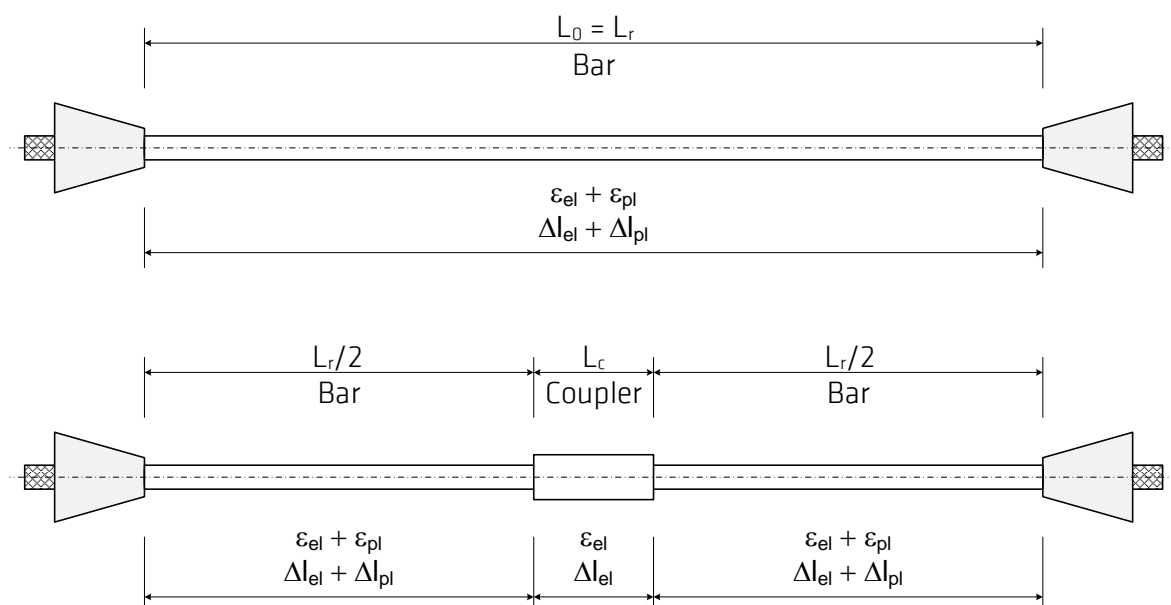


Figure 7: Schematic illustration of strain and deformation components at different parts of the specimen without and with coupler system in the area of the specimen located between the clamping

Deformations

- The deformations of reinforcement bar and coupler are a result of the strains and the corresponding length of bar and coupler.
- Elastic deformations are generated at the begin of the test (Phase I). After exceeding the yield strength (Phase II) plastic deformations are commonly generated almost exclusively at the bars, as illustrated in Figure 8.
- Following that high-speed tensile tests are defined primarily by the plastic deformation at the bars. They represent the largest part of the deformations in Phase II.

- The elastic strains at the bars and at the coupler lead to elastic deformations. Elastic deformations at the bars are typically larger compared to the coupler, since the length of the coupler is smaller compared to the bars and the diameter of the coupler is mostly larger.
- Therefore, following conclusive statements can be done for the deformation components in high-speed tensile tests on reinforcement coupler systems:

$$\Delta L_{\text{tot}} = \Delta l_{\text{el}} + \Delta l_{\text{pl}}$$

$$\Delta L_{\text{tot}} = \Delta L^{\text{Bar}} + \Delta L^{\text{Coup}}$$

$$\Delta L^{\text{Bar}} \gg \Delta L^{\text{Coup}}$$

$$\text{Phase I: } \Delta l_{\text{el}} = \Delta l_{\text{el}}^{\text{Bar}} + \Delta l_{\text{el}}^{\text{Coup}}$$

$$\text{Phase II: } \Delta l_{\text{pl}} = \Delta l_{\text{pl}}^{\text{Bar}}$$

$$\Delta l_{\text{pl}}^{\text{Coup}} \sim 0$$

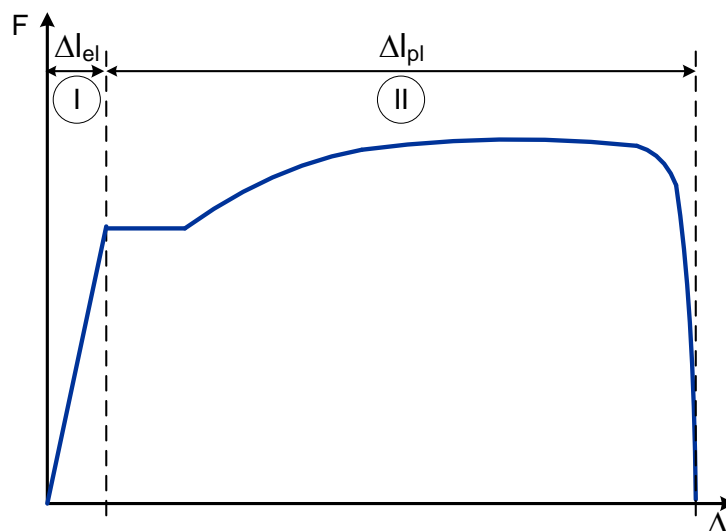


Figure 8: Schematic force-deformation-relationship for a high-speed tension test with the region of elastic deformations (phase I) and region of plastic deformations (phase II)

Strain rates

- High-speed tensile tests executed by a servo hydraulic test facility with a clamping device for a fixed clamping of the specimen before start of testing show a characteristic development of strain rates. The related relationship of strain rate and time is schematically illustrated in Figure 9.

- A starting range with increasing strain rate and following stable range with constant strain rate is typical for a high-speed tensile test. The accelerating phase of the test facility may be one of the reasons for the starting range.
- The following range of constant strain rate is quasi defined only by the plastic strains or plastic deformations of Phase II generated at the reinforcement bars. This area represents almost the complete duration of the test.
- The range with constant strain rate is usually reached almost after Phase I within Phase II.

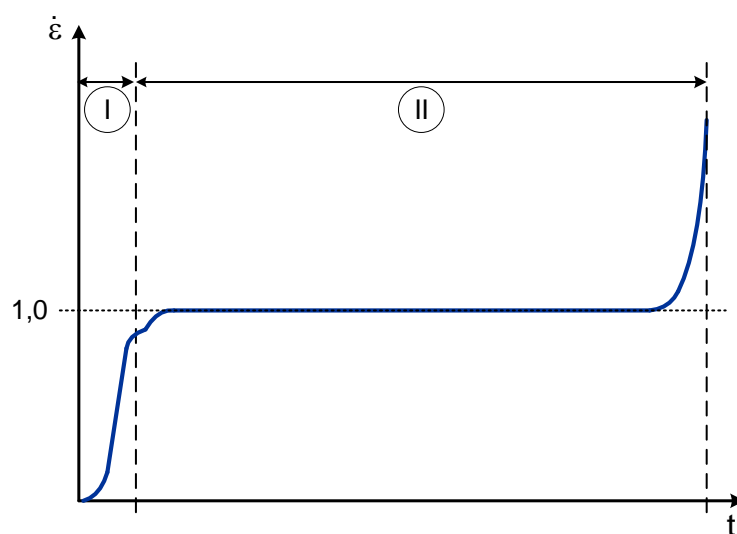


Figure 9: Typical development of strain rate over time at high-speed tensile tests on specimen of reinforcement bar coupler systems

- Aim of the high-speed tensile test is to reach a constant average strain rate of $\dot{\epsilon} = 1.0 \text{ s}^{-1}$ during the high-speed tensile test. This requirement applies for high-speed reference tests as well as for tests of coupled specimen. This value corresponds to the requirements in ETC-C [9] and in EDF [8].

$$\dot{\epsilon} = 1.0 \text{ s}^{-1}$$

- A tolerance for the constant strain rate of $\pm 20 \%$ is acceptable.
- Therefore, a constant test velocity needs to be adjusted in such way that a constant strain rate of $\dot{\epsilon}_{pl} = 1.0 \text{ s}^{-1}$ will be achieved in the plastic area of Phase II. This means a constant strain rate of 1.0 s^{-1} within the reinforcement bars, because the constant strain rate is quasi defined only by plastic deformation of the bars.

$$\dot{\epsilon}_{pl} = 1.0 \text{ s}^{-1}$$

- The average strain rate which occurs in the material can be determined based on a strain increment which is calculated by dividing the measured elongation difference by the initial length:

$$\Delta \varepsilon = \Delta L / L$$

- In the range of elastic and plastic stretching of the reinforcement bar, the strain rate can be defined by using the duration of the time interval Δt :

$$\dot{\varepsilon} = \Delta \varepsilon / \Delta t$$

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{\Delta L}{L} \cdot \frac{1}{\Delta t} = \frac{v_z}{L}$$

- Following the requirement to achieve a constant strain rate in the plastic range of the reinforcement steel it leads to the relationship:

$$\dot{\varepsilon}_{pl} = \frac{\Delta l_{pl}^{Bar}}{L_r} \cdot \frac{1}{\Delta t} = \frac{v_z}{L_r} = 1.0 \text{ s}^{-1}$$

- For specimens with mechanical splice the preset velocity of the piston rod should be calculated as follows:

$$v_z = \dot{\varepsilon}_{pl} \cdot L_r \text{ [mm/s]}$$

$v_z = \dot{\varepsilon} \cdot L_r \text{ [mm/s]} \quad \text{with } \dot{\varepsilon} = 1.0 \text{ s}^{-1} \text{ and } L_r = L_0 - L_c$

- For specimens without mechanical splice, like reference bars, the preset velocity of the piston rod should be calculated as follows:

$$v_z = \dot{\varepsilon} \cdot L_r \text{ [mm/s]} \quad \text{with } \dot{\varepsilon} = 1.0 \text{ s}^{-1} \text{ and } L_r = L_0$$

- For specimens with mechanical splice for diameter transition, like coupler for the connection of reinforcement bars of different diameter, the preset velocity of the piston rod should be calculated as follows:

$$v_z = \dot{\varepsilon} \cdot L_r / 2 \text{ [mm/s]} \quad \text{with } \dot{\varepsilon} = 1.0 \text{ s}^{-1}$$

and $L_r / 2$ = free length of the thinner reinforcement bar

- After the test, the plastic deformations of the bars as well as of the coupler should be measured. In case the coupler shows relevant plastic deformations, an adjustment of the test velocity can be required.

8.3. Comparability of test results

The comparability of the results needs to be guaranteed to permit the assessment and evaluation of the test results of different high-speed tensile tests. This applies for different specimens with coupler systems but also for the comparison with the reference test on pure reinforcement bars. Parameters of the specimen which can differ are:

- Different diameters of the bars
- Different lengths of the specimens
- Different types of couplers
- Coupler systems from different manufacturers

This concerns especially the tests of specimen or coupler systems from different manufacturers. Therefore, the following points should be considered:

- Only stress-strain-curves from tests with the same or nearly the same strain rate can be compared.
- Therefore, the same strain rate of 1.0 s^{-1} shall be achieved in all high-speed tensile tests, as specified also by ETC-C [9] and EDF [8].
- This strain rate of 1.0 s^{-1} will be generated only at the reinforcement bars, since nearly no plastic deformation will be generated in the coupler, as described in section 8.2 and as confirmed by a large number of high-speed tensile tests.
- Therefore, the test velocity v_z has to be calculated based on the length of the bars and without the coupler (L_r), that is:

$$v_z = \dot{\epsilon} \cdot L_r [\text{mm/s}] \quad \text{with } \dot{\epsilon} = 1.0 \text{ s}^{-1}$$

- A special case in this context is that of coupler elements for reinforcement bars with different diameters (**Mechanical splice for diameter transition**). The strain rate will be typically generated only in the reinforcement bar with smaller diameter. This has to be considered for the calculation of the test velocity v_z , as specified in section 8.2.

An exemplary calculation to illustrate this issue is given in Appendix 1 for four different specimen geometries and with two different methods of calculation of test velocity v_z .

9. Testing procedure

9.1. Testing program

For the test campaign of a single type of coupler with a single geometry, a test series consisting of static and dynamic tests on reference bars and bars with coupler system is required as given in Table 3. Wherever different types or geometries of coupler are to be tested, an additional test series must be performed for each variation.

Table 3: Overview of required specimen for one test series

Type of specimen	Type of test	Quantity	Remarks
Reference bar	static	2	$v_z = 0.00015 \cdot L_0$
Reference bar	dynamic	2	$v_z = \dot{\epsilon} \cdot L_0$
Rebar coupler system	dynamic	5	$v_z = \dot{\epsilon} \cdot L_r$
Reference bar	reserve	≥ 1	
Rebar coupler system	reserve	≥ 2	

- All specimens within each of the test series shall have the same geometry.

9.2. Test procedure and parameters

The procedure for execution of the static and dynamic tests is specified respectively in the following sections.

9.2.1. Static tensile tests

The process for the reference tests is as follows:

- 1) Two reference bars with a length of L_t (commonly of about 1250 mm as used at the BAM) to be used for static tensile tests. Intervals shall be marked for a measurement of the permanent elongation on the reinforcement bars (30 mm at BAM).
- 2) Installation of the reference bars into the testing machine as shown in Figure 5.
- 3) The distance L_0 between the two clamps shall be measured as shown in Figure 1. L_0 shall be kept almost the same in all tests.
- 4) The static loading speed $v_z = 0.00015 \cdot L_0$ [mm/s] shall be set in displacement control. This test speed is based on the tensile speed specified in ISO 6892-1: 2019 [3] (procedure B 10.3.3) which corresponds to approx. 31.5 N/mm² per second. For a specimen length of $L_0 = 1000$ mm, the static loading speed results in $v_z = 0.15$ mm/s, to be sustained until the specimen breaks. The test shall therefore be performed under displacement control for the piston rod of the hydraulic cylinder.
- 5) During the test, the piston force and the deformation shall be permanently recorded with a sampling rate of at least 50 Hz.

9.2.2. High-speed tensile tests

During the high-speed tensile tests, a constant displacement velocity of the piston rod v_z should be reached. The value of the target velocity shall be chosen in such a way, that an average strain rate $\dot{\epsilon}$ of about 1.0 s^{-1} is reached in the reinforcement bar, see also section 8.2. These testing principles are adapted amongst others from ETC-C 2012 Edition Part 2 [9]. Therefore, the value of strain rate corresponds to the value given in ETC-C 2012 Edition Part 2 [9] for high velocity tensile loading tests.

To guarantee a comparability of the strain rate in the reinforcement steel of specimens with different coupler length or with specimens of different length, the pre-set velocity of the piston rod is calculated under the assumption that the stretching in the coupler is negligible and only the reinforcement part between the clamping jaws and the coupler will be stretched. Vast experience with high-speed tensile tests on reinforcement coupler systems have shown and confirmed that nearly no stretching occurs over the coupler length when loaded up to failure.

The preset velocity of the piston rod shall therefore be calculated as follows:

$$v_z = \dot{\epsilon} \cdot L_r \text{ [mm/s]} \quad \text{with } \dot{\epsilon} = 1.0 \text{ s}^{-1} \text{ and } L_r = L_0 - L_c$$

The process for the dynamic tests is as follows:

- 1) Five assembled specimens with coupler with a total length of L_t (usually of about 1250 mm at BAM) are to be used for high speed tensile test. Intervals shall be marked for a measurement of the permanent elongation (30 mm at BAM) over the reinforcement bars on both sides (two times on $L_r/2$), which will divide the reinforcement bar in the two sections into several original distances.
- 2) Installation of the assembled specimen with coupler into the testing machine as shown in Figure 5.
- 3) The distance L_0 between the two clamps and the coupler length L_c shall be measured as shown in Figure 3. The length of the reinforcement steel of the specimen L_r is calculated by $L_r = L_0 - L_c$. L_0 shall be kept almost the same in all tests.
- 4) The dynamic loading speed $v_z = L_r/1\text{s}$ shall be set in displacement control and the loading shall be sustained until the specimen breaks. The controlled variable should be the displacement of the piston rod of the hydraulic cylinder.
- 5) During the test, the piston force and the deformation are permanently recorded with a sample rate of at least 5 kHz.

10. Test results and evaluation

10.1. Test results (general)

10.1.1. Reference bars

The results of the tests for the reference bars shall include relationships and diagrams for:

- Stress vs. strain
- Force vs. time (only for the high-speed test)
- Displacement W_1 of the piston rod vs. time (only for the high-speed test)
- Velocity of the piston rod vs. time (only for the high-speed test)
- Strain rate vs. time (only for the high-speed test)

Furthermore, the characteristic values shall be determined for the following parameters:

Table 4: Table for characteristic values to be determined for reference bars

REFERENCE Marking	v_z [mm/s]	$A_g=A_{\max F}$ [%]	A_{gt} [%]	σ_{\max} [N/mm ²]	Failure [Locat.]	Remarks

- Achieved average velocity v_z [mm/s]
- Maximum stress σ_{\max} [N/mm²]

$$\sigma_z = F/A_N \quad [\text{N/mm}^2]$$

- Non-proportional elongation A_g [%]; calculated according to ISO 15630-1 [4]

$$A_g = A_{\max F} \quad [\%]$$

- Total elongation at maximum force A_{gt} [%]; calculated according to ISO 15630-1 [4]

$$A_{gt} = A_g + \sigma_{\max}/2000 \quad [\text{N/mm}^2; \%]$$

- Documentation of the failure mode and location

10.1.2. Rebar coupler systems

The results of the tests for the rebar coupler systems shall include relationships and diagrams for:

- Stress vs. strain
- Force vs. time
- Displacement W_1 of the piston rod vs. time
- Velocity of the piston rod vs. time
- Strain rate vs. time

Furthermore, the characteristic values shall be determined for the following parameters:

Table 5: Table for characteristic values which needs to be determined for rebar coupler specimen

Coupler System	v_z [mm/s]	$A_{\max F}=A_g$ [%]	$A_{\max F}=A_g$ [%]	σ_{\max} [N/mm ²]	A_{gt} [%]	A_{gt} [%]	Failure [Locat.]	Remarks
Marking		Side A	Side B		Side A	Side B		

- Achieved average velocity v_z [mm/s]
- Maximum stress σ_{\max} [N/mm²]

$$\sigma_z = F/A_N \quad [\text{N/mm}^2]$$

- Non-proportional elongation A_g [%]; calculated according to ISO 15630-1 [4]

$$A_g = A_{\max F} \quad [\%]$$

- Calculated for both the broken and the unbroken side

- Total elongation at maximum force A_{gt} [%]; calculated per ISO 15630-1 [4]

$$A_{gt} = A_g + \sigma_{\max}/2000 \quad [\text{N/mm}^2; \%]$$

- Documentation of the failure mode and location
- Dimensions of the coupler after the test

10.2. Failure mode and location of fracture

10.2.1. Reference bars

- The location of the failure (bar/ clamping zone); assessed according to ISO 15630-1 [4] and ISO 15835-2:2009 [6]
 - Clamping zone (d_1)
 - Measurement range (d_2)
 - Slip at clamping zone (X_1 , X_2)
- The mode of failure shall be identified as either:
 - Ductile failure, or
 - Brittle failure

10.2.2. Rebar coupler systems

- The location of the failure (bar/ coupler/ mechanical splice/ clamping zone); assessed according to ISO 15630-1 [4] and ISO 15835-2:2009 [6]
 - Clamping zone (d_1)
 - Measurement range (d_2)
 - Coupler zone (d_3), defining the mechanical splice length
 - Coupler length (L_c)
 - Slip at clamping zone (X_1 , X_2)
 - Slip at coupler
- The mode of failure shall be identified as either:
 - Ductile failure, or
 - Brittle failure

10.3. Evaluation of test results

10.3.1. Reference bars

The results of the tests for the reference bars shall be evaluated as follows:

- Check if no relevant slip has occurred at the clamping zone of the specimen
- Check whether the achieved average strain rate attains $\dot{\epsilon} = 1.0 \text{ s}^{-1}$ (tolerance $\pm 20 \%$) in the high-speed tests
- Verify the difference in maximum stress σ_{\max} between the static and high-speed tests on reference bars
- Is the non-proportional elongation A_{gt} in line with the specification provided by ETC-C 2012 Edition Part 2 (A_{gt} greater than 5.0 %) [9] in the high-speed tests
- Is the non-proportional elongation A_{gt} in line with the specification provided by BS4449 (A_{gt} greater 7.5 %) [7] in the high-speed tests

- Classification of mode of fracture (brittle fracture, ductile fracture)
 - In case the mode of fracture is not ductile it shall be stated in the test report.
- Failure location, rebar or clamping zone (see section 6.1.1)
 - In case the requirements for the location d_1 of the failure are not met it should be stated in the test report.

10.3.2. Rebar coupler systems

The results of the tests for the rebar coupler systems shall be evaluated as follows:

- Check if no relevant slip has occurred at the clamping zone of the specimen
- Check if no relevant slip has occurred at the coupler of the specimen
- Check whether the achieved average strain rate attains $\dot{\epsilon} = 1.0 \text{ s}^{-1}$ (tolerance $\pm 20 \%$)
- Verify the difference in maximum stress σ_{\max} between high-speed tests on rebar coupler systems and reference bars
- Is the non-proportional elongation A_{gt} in line with the specification provided by ETC-C 2012 Edition Part 2 (A_{gt} greater than 5.0 %) [9]
- Are the non-proportional elongation A_{gt} in line with the specification provided by BS4449 (A_{gt} greater 7.5 %) [7]
- Classification of mode of fracture (brittle fracture, ductile fracture)
 - In case the mode of fracture is not ductile it shall be noted in the test report.
- Failure location, rebar, clamping zone or coupler zone (see section 6.1.2)
 - In case the requirements for the location d_1 and d_3 of the failure are not met it should be stated in the test report.
 - In case the required value for d_2 cannot be met on the broken side the unbroken side of the specimen can be used for evaluation alternatively. This shall be stated accordingly in the test report.
 - In case the failure takes place within the coupler it shall be highlighted accordingly in the test report.
- Dimensions and condition of the coupler after test
 - In case the coupler exhibits any kind of damaged condition it shall be stated accordingly in the test report.
 - In case the coupler exhibits relevant plastic deformation, it shall be stated adequately in the test report. Furthermore, an adjustment of the test velocity may be required,

11. Test report

The test report shall contain at least the following information:

- All results described in sections 10.1 to 10.3
- Date of the tests
- Reference used for the tests (applied Test Specification)
- Name of the laboratory
- Name of the organisation ordering the test (including the date)
- Related specification standard for, and grade of, reinforcement with which the test piece was prepared
- Rib geometry of the bar
- Name of the supplier of the coupler and markings on the coupler (size, type and batch number, legibility of batch number)
- Assembly instructions provided by the supplier of the coupler
- Inspection documentation or certificate for reinforcement bars
- Details of assembly of the test piece(s) (e.g. torque value used, temperature)
- Values for geometry of the specimens
- Diameter and length of the coupler
- Identification marks of each specimen from test laboratory
- Tensile strength σ_{\max}
- Name of the laboratory operator
- Name and signature of the person responsible for preparation of the test report

12. Appendix 1: Example for comparability

To illustrate the issue of comparable tests, an exemplary calculation is given in Table 6 for four different specimen geometries and with two different methods of calculation of test velocity v_z . All geometries are shown in Figure 10. The resulting strain rates in the high-speed tensile tests are schematically illustrated in Figure 11.

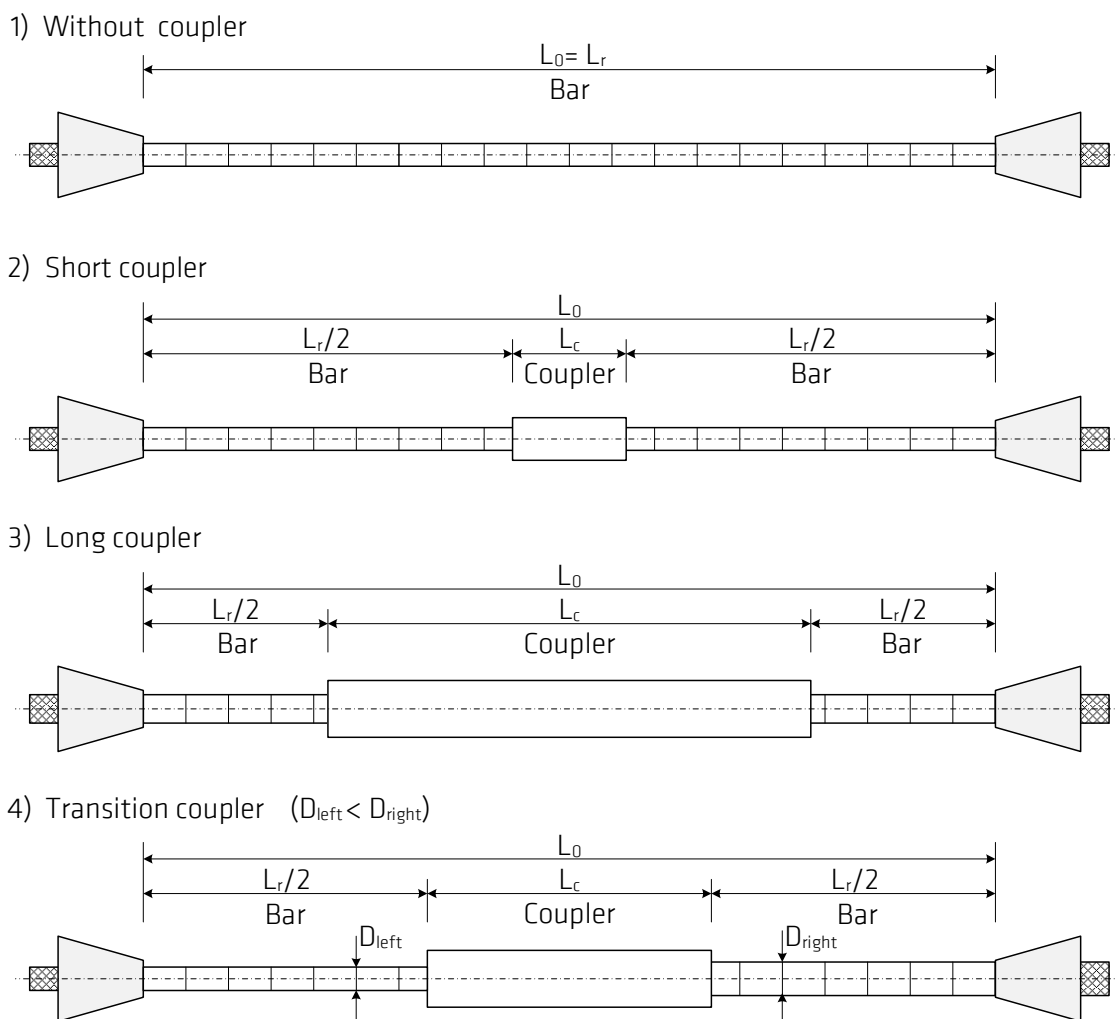


Figure 10: Schematic illustration of four different specimen geometries with no, short, long and transition coupler

Table 6: Exemplary calculation for four different specimen geometries and two methods for calculation the test velocity

Value	1) No coupler	2) Short coupler	3) Long coupler	4) Transition c.
L ₀ [m]	1.0 m	1.0 m	1.0 m	1.0 m
L _c [m]	0.0 m	0.1 m	0.5 m	0.3
L _r = L ₀ - L _c [m]	1.0 m	0.9 m	0.5 m	0.35*
Case A: v _z based on L _r				
v _z = L _r x ε̇ [m/s]	1.0 m/s	0.9 m/s	0.5 m/s	0.35 m/s
ε̇ _{pl} (rebar) = v _z / L _r [1/s]	<u>1.0</u> s ⁻¹	<u>1.0</u> s ⁻¹	<u>1.0</u> s ⁻¹	<u>1.0</u> s ⁻¹
Result	Test results and strain rates comparable!			
Case B: v _z based on L ₀				
v _z = L ₀ x ε̇ [m/s]	1.0 m/s	1.0 m/s	1.0 m/s	1.0 m/s
ε̇ _{pl} (rebar) = v _z / L _r [1/s]	<u>1.00</u> s ⁻¹	<u>1.11</u> s ⁻¹	<u>2.00</u> s ⁻¹	<u>2.90</u> s ⁻¹
Result	Test results and strain rates <u>not</u> comparable!			

* For transition coupler only free length of the thinner reinforcement bar must be used!

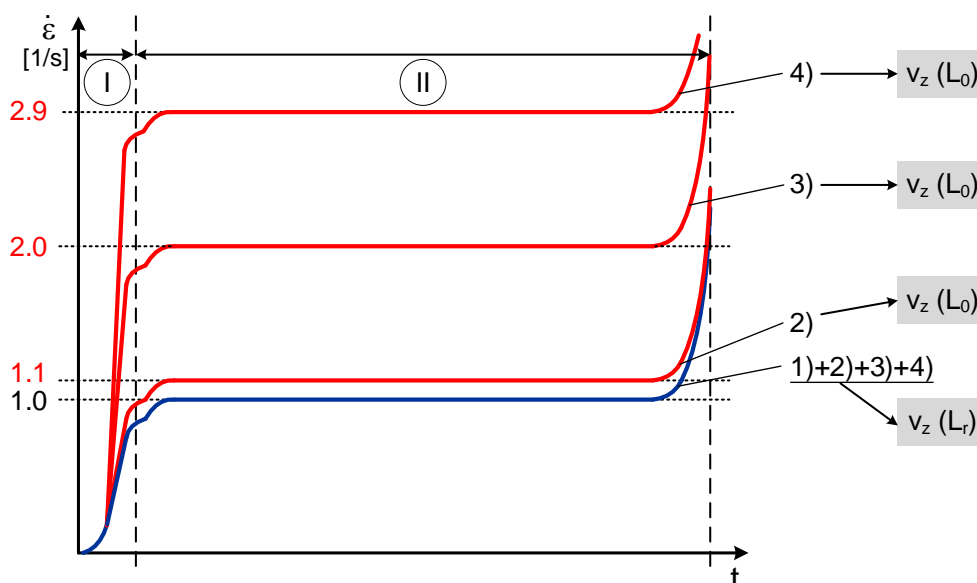


Figure 11: Exemplary illustration of resulting strain rates for four different specimen geometries with two methods for calculation the test velocity

The results in Table 6 and in Figure 11 illustrate very clear, that for comparable test results the same strain rate is needed in the high-speed tensile tests. For specimen with mechanical splice the test velocity is recommended to be defined based on L_r to achieve the same strain rate in the reinforcement bars.

$$v_z = \dot{\epsilon} \cdot L_r \text{ [mm/s]} \quad \text{with } \dot{\epsilon} = 1.0 \text{ s}^{-1}$$

- This definition follows the prescription used by EDF [8]
- The related strain rate is independent from L_c and L_0
- An average strain rate of 1.0 s^{-1} will be achieved. This corresponds to requirements in ETC-C [9] and EDF [8].
- The comparability of test results is thereby granted