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Investigations on the Shear Behavior of Bridge Girders made of Normal and Ultra-High Performance Fiber-Reinforced Concrete

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Abstract

To further analyze the shear behavior of continuous prestressed bridges, two research projects are currently being examined at the Chair of Concrete and Masonry Structures of TUM. While one project focuses on the actual bearing capacity of older existing bridges, the other one deals with the development of prefabricated prestressed UHPFRC I-beams utilizing different reinforcing concepts and materials. Alongside complex numerical investigations, a comprehensive experimental test series will be carried out. For all tests an innovative experimental setup is being developed, which allows full scale testing of concrete beams at reduced length using the substructure technique.
On the one hand the shear resistance of slender prestressed ultra-high performance fiber-reinforced concrete (UHPFRC) bridge girders with very thin webs is investigated. For these I-shaped beams the shear behavior for different types of shear reinforcement, as well as the size effect for different cross-section heights is investigated.
Furthermore, the influence of various types of shear reinforcement, especially outdated stirrups no longer permitted by current standards, on the shear capacity of existing bridges is being researched. In detail these stirrups, which can often be found in older bridges, are not closed or have insufficient overlap length. As the shear design is a major issue for the re-analyses of bridges in Germany where the provided stirrups do not meet current requirements, the impact of the stirrup geometry on the shear capacity of bridge girders made of normal strength concrete has to be investigated.
The paper generally explains the above mentioned research projects and presents the results of preliminary investigations.

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Keywords: UHPFRC; shear behavior; FEM; material modeling; testing; bridge girders; re-analyses; stirrup types;

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1. Introduction

The shear behavior of concrete structures is a fundamental research topic, which was already scientifically examined for many years, starting with the early work of Hennebique, Ritter and Mörsch in the 19th century. Nevertheless, some questions regarding the shear behavior in reinforced concrete (RC) elements, specifically the force flow through the member and across cracks at ultimate state, can still be answered only partially. Although the fundamental correlations and load supporting components for the shear design of structures are meanwhile well known, there is a continuing debate on their respective contributions and on convenient approaches for the design.

Recently, new issues arose due to the use of new materials such as Ultra-High Performance fiber-reinforced concrete and – especially in Germany - the requirement for more sophisticated calculation approaches for the re-design of existing bridges.

In this context, two research projects are ongoing at the Chair of Concrete and Masonry Structures of TUM (Technical University of Munich), which shall be presented in this paper. While one project focuses on the influence of out-dated stirrup types on the shear capacity of older existing bridges, the other one deals with the development of prefabricated prestressed UHPFRC I-beams utilizing different reinforcing concepts and materials. In the scope of this paper, interim results of numerical studies regarding these two different issues will be presented and an outlook for tests using an innovative experimental setup is given.

2. General aspects of the shear behavior of bridge girders

2.1. Overview

Usually, the design of bridge girders is determined by the corresponding bending loads, whereas for compact or strongly profiled cross-sections the shear resistance may govern. In these cases, the diagonal tension failure is normally the typical mode of failure, which occurs if a principal stress component exceeds the tensile strength of the concrete and a redistribution of stresses to the web reinforcement is not possible. Depending on the amount of stirrups, the shear failure of a beam is likely to occur suddenly and without much advance notice. Therefore this brittle type of failure has to be avoided.

For the uncracked state the principal stress direction in the concrete can be easily calculated, using the governing equations and by introducing shear stresses as an auxiliary quantity for the transformation from a global into a rotated local coordinate system. For cracked sections (state II) it then becomes more complicated, as different bearing mechanisms have to develop to find equilibrium again. The main mechanisms for the transmission of shear stresses in the cracked state (for beams without shear reinforcement) are widely known: the contribution of the compressive concrete zone, crack friction and aggregate interlock between the crack edges, dowel effect of the longitudinal reinforcement and tensile forces in the fracture zone

For girders with stirrups or steel fiber reinforcement in the web, an equivalent contact ratio is added. The problem is to verify the appropriate quantitative contributions for different circumstances such as the cross sectional dimensions, the type of loading, the geometry and the type and amount of concrete and (fiber-) reinforcement. Therefore, further considerations for specific cases have to be undertaken, to broaden experience and expertise in this field. In this context, two R&D projects are ongoing at TUM, which shall be described in the following.

2.2. Investigations on prestressed bridge girders made of UHPFRC

Ultra-High performance fiber-reinforced concrete is an advanced cementitious high quality material with a characteristic compressive strength of at least 150 MPa, which allows the realization of extremely thin and durable structural elements. Through the addition of steel fibers, the concrete gains tensile strength and the desired ductility is ensured. Hence the use of conventional reinforcement can be avoided in many areas. The result is efficient and solid light-weight structures which are perfectly suited for the application in prefabricated bridge construction.

Due to the characteristics of UHPFRC, the cross sectional dimensions usually deviate from standard concrete construction and as a result, the load bearing behavior might be different. Besides that, through the use of steel fiber reinforcement, additional questions and characteristics arise, which have to be considered in the design. Using

UHPFRC for bridge girders allows for the realization of very thin webs with thicknesses around 50 mm for standard cross section heights of approximately 1.50 m, which is a quarter of the usual thickness using normal strength concrete. For these beams, the shear capacity of the web is the governing design issue. Hence, further investigations on the shear behavior for different types of shear reinforcement (variation of the fiber content and type, additional stirrups etc.) are being undertaken numerically and experimentally. In this regard, the size effect will also be examined, through the use of specimens with different cross section heights (from 0.6 m to 1.2 m) for all tests. As previous research projects [1] show, there is a pronounced size effect for slender UHPFRC beams without shear reinforcement, meaning that the shear capacity decreases when the cross section height increases. The size effect for shear is of particular interest for UHPFRC, since the effective fracture zone becomes smaller with higher concrete strength. This also means that the energy release which is caused by the growth of a shear crack might lead to a brittle failure without advance notice. Therefore more research is necessary to investigate whether stirrups can suppress the size effect and to define a minimum fiber or shear reinforcement ratio for ductile behavior. Another aim of the research project is to bring UHPFRC more into construction practice. In the scope of the research project at TUM, durable and innovative precast girders for single and multi-span bridges with average spans of around 35 m will be developed. Finally, the results of this research project are planned to be directly integrated in a full-scale pilot application which will be accompanied by an extensive monitoring scheme.

The research project is a cooperation project of the Technical University of Munich (TUM), the Munich University of Applied Sciences and the engineering office SSF Ingenieure AG.

2.3. Consideration of outdated stirrups for the re-analyses of bridges in Germany

The requirements for existing bridges in Germany have increased considerably in the past few years, due to rising traffic volumes. Many older bridges were designed for load models which do not fulfill today's specifications. Furthermore, the design values for the shear capacity have undergone several modifications over time. As a consequence, re-analyses of these bridges often results in a significantly higher amount of necessary shear reinforcement and the design can't be fulfilled according to current standards. Within the framework of a major research project for the German Federal Highway Research Institute (BASt), advanced design methods for the evaluation of the shear and torsional stress capacity of existing bridges shall be derived and verified, which are able to consider special load reserves in comparison to the current technical regulations.

In connection with this, one issue is the consideration of shear reinforcement types which deviate from the current specifications. According to German standards [2] it is required that stirrups be closed in the compressive and tensile concrete zone, except in the case of T-beams where exceptions might be allowed under certain conditions. All types of shear reinforcement have to be anchored between the centroidal axis and upper edge of the compressive zone, and straight rod ends are also not allowed. With regard to the re-analyses of existing bridges, different outdated types of stirrups can be found: push-in-stirrups (which were only inserted into the top), two part stirrups with short overlap lengths, or stirrups with straight rod ends which are not closed at the upper side. These types of shear reinforcement may not be taken into account for the evaluation of the shear capacity according to German standards. The question therefore is how these modifications change the load bearing characteristics for shear and in which way it is justified to take this web reinforcement into account. [3]

There are some experimental investigations on the effect of two part stirrups with short overlap lengths [4], which show that the shear capacity according to design standards can also be reached if the overlap length of the stirrups is significantly reduced. Only a few investigations exist which deal with the influence of different types of shear reinforcement [5], [6], [7], [8], [9] (for example for stirrups which are not closed), where the main focus was on the influence of fractured stirrups. Thus, further research in the form of experimental and numerical investigations is urgently needed here, to consider these special conditions.

3. Numerical investigations

3.1. Modelling approaches

To undertake further research with regard to the above mentioned issues, extensive numerical investigations were conducted. For all calculations the program ANSYS together with a library for nonlinear continuum mechanical based material models called MULTIPLAS was used. A hardening/softening material model which is based on a Menetrey-William yield surface [10] with a fracture energy based regularization method was applied. The reinforcement was modelled discretely. While the approach of a rigid connection between reinforcement and concrete was sufficient for the analyses of the UHPFRC beams, the bond behavior between stirrups and concrete had to be taken into account for the investigation of the influence of different shear reinforcement types. All finite element models were validated on the basis of experimental results from literature.

3.2. Numerical Studies on UHPFRC bridge girders

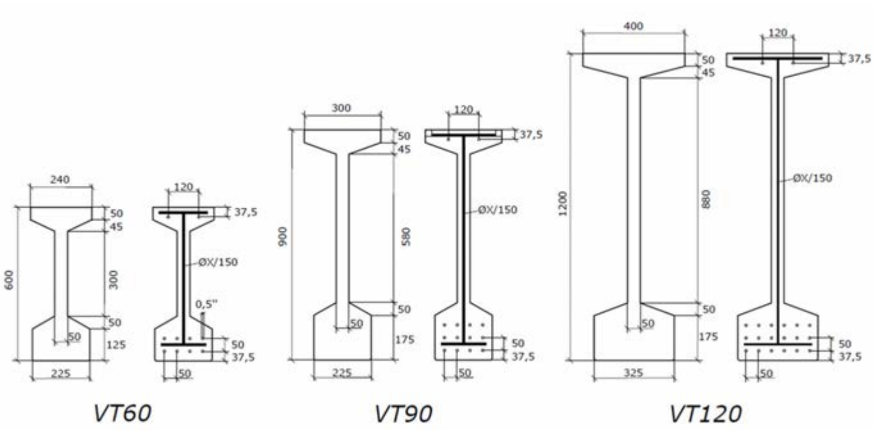

Figure 1: Cross-sectional dimensions for the numerical parameter study

To verify the main parameters which influence the load bearing behavior of UHPFRC bridge girders in shear, first of all a detailed numerical parameter study was made. The study included a variation of the cross section height, the amount of steel fiber reinforcement, the shear reinforcement ratio in the web and the degree of prestressing. Figure 1 gives an overview of the dimensions for the different cross section types. The distance between the stirrups was kept constant with a value of 15 cm and the prestress in the cross sections was chosen such that the normal stresses due to the normal force component of the prestress were constant as well, with a value of about 15.9 MPa (8 to 18 strands depending on the cross section height).

Figure 2 summarizes the main results of the study, whereby the respective nomenclatures indicate the cross section height in cm (VT**X**), the amount of steel fiber reinforcement in Vol. % (M**X**), the diameter of the stirrups (Q**X**) and the degree of prestressing (P**X**).

The results show that the load carrying capacity rises with increasing cross section height and with an increase of the amount of shear reinforcement. Additional shear reinforcement leads to more ductile behavior of the specimen, due to yielding of the stirrups. If the amount of shear reinforcement is quite high, the mode of failure does not correspond to a pure shear failure in the web anymore, but to a combined shear and flexural failure. The degree of prestressing only has a slight effect on the shear capacity, but clearly affects the first crack initiation. A higher fiber content increases the failure load noticeably and of course also leads to a more ductile behavior. In order to examine the size effect for different cross section heights, which were clearly identified in previous research work [1], further simulations have to be undertaken, as no clear trend could be observed.

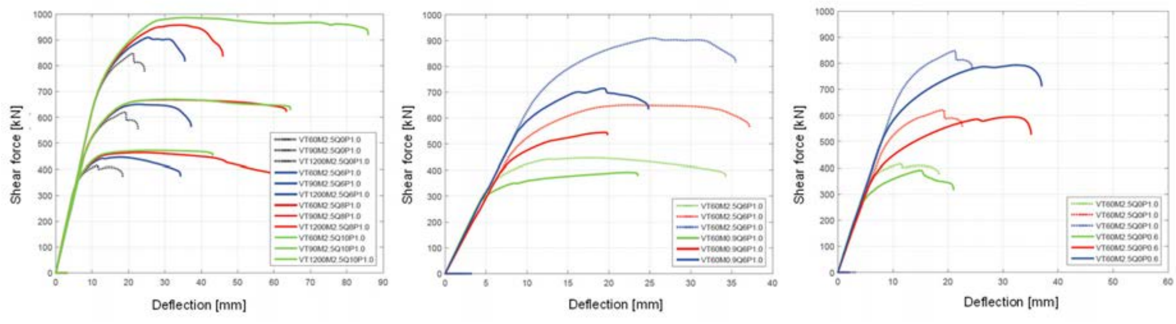

Figure 2: Results of the parameter study: (a) influence of shear reinforcement ratio (b) influence of steel fiber content (c) influence of prestress for different cross section heights

On the basis of the above described parameter study, the cross section geometry of the UHPFRC bridge girder was optimized. For the desired average span of about 35 m, precast girders made of normal strength concrete (NSC) with pretensioned reinforcement are often used. To enable a direct comparison, a typical bridge cross-section was assumed and finite element simulations were undertaken for both alternatives. Table 1 gives an overview of the related parameters:

Table 1. Cross section parameters for a typical NSC bridge girder and an optimized bridge girder made of UHPFRC

	NSC girder	UHPFRC girder
cross-section height	1.40 m	1.50 m
pretensioned reinforcement	32 ∅ 12,5 mm	32 ∅ 12,5 mm
conventional reinforcement in chords	4 ∅ 16 + 14 ∅ 12	2 ∅ 10
shear reinforcement	2 x ∅ 16 / 10 cm	∅ 10 / 15 cm

By comparing the two systems, it is clearly visible that the UHPFRC girder cross-section is much slender than the one made out of NSC. Using the UHPFRC system, around 37 % of the weight can be saved and the excellent durability properties of the material can be used. To directly compare the load bearing behavior and the stiffness of the two systems, a 3-point bending test for a 10 m long beam was performed numerically, modelling only half of the system due to the symmetry of the system (see Figure 3).

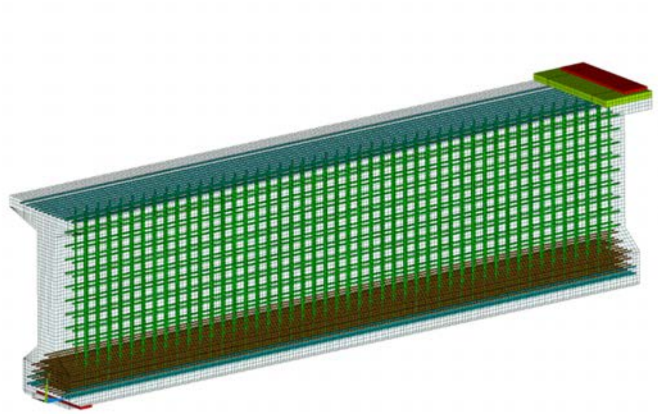

Figure 3: 3D finite-element-model for the simulation of a 3-point-bending-test utilizing the symmetry of the system (here shown for the NSC cross-section)

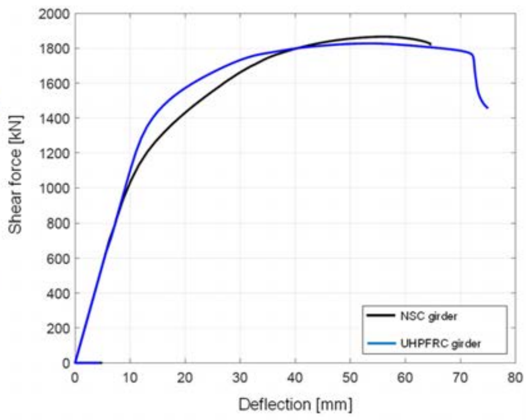

Figure 4: Comparison of the shear force deflection curves for a NSC and a UHPFRC girder

Looking at the resulting shear load-deflection curves for the two systems (see Figure 4) it can be seen that the stiffness behavior before initial crack formation is similar for both systems. This can be explained by a more or less similar bending stiffness, EI, since the elastic modulus of the assumed coarse grain UHPFRC is approximately 51,000 MPa compared to 37,000 MPa for NSC (assumed value for a standard C 50/60 concrete) and the moment of inertia is around 13 % less for the UHPFRC cross section. The results of the simulations also show that the types of failure slightly differ from each other. For both variants, plastic strains representing bending cracks are observed first. At ultimate limit state the UHPFRC girder clearly fails due to diagonal shear in the thin web, whereas for the NSC girder a flexural failure with the formation of shear cracks (which indicates, that the shear capacity is very close to the flexural capacity) seems to occur. The ultimate loads for both types are almost identical. Due to better utilization of the pretensioned reinforcement for the UHPFRC beam, the pretension is more effective and the initial crack formation is delayed.

3.3. Numerical investigations on beams with outdated stirrup types

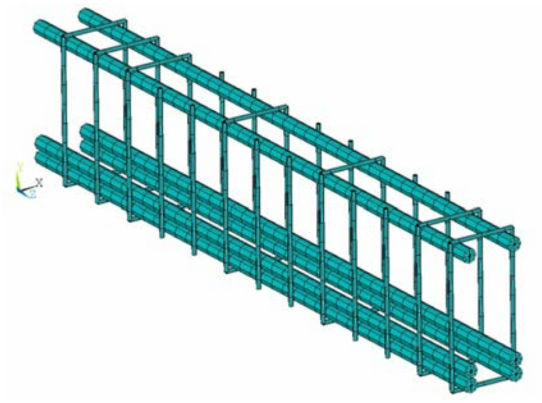

Figure 5: Discrete modeling of the modified reinforcement with beam elements (half system because of symmetry) considering the bond behavior of the stirrups

Initially, the effects of outdated stirrup types on the load bearing behavior of beams in shear were investigated through finite-element-calculations. To model the behavior of stirrups with straight rod ends under realistic conditions, it is necessary to take into account the bond behavior between reinforcement and concrete, as the normal forces in the vertical parts of the stirrups are not anchored to the flanges, but have to build up over a certain development length. As this approach is not easy to model numerically, the calculations have to be carefully validated in detail. Therefore the behavior of stirrups which partially exist of vertical members only (compare Figure 5) was studied by modelling experiments from literature. For this purpose the test series of [8] was used, where the effects of corrosion on stirrup anchorage by replacing up to 75 % of stirrups with straight-legged shear reinforcement were investigated. Although this is a different topic, the test results are useful for the given problem of substandard shear reinforcement types.

For the numerical investigations 3 tests with different shear reinforcement in the cross sections from [8] were used. The chosen tests were 3-point-bending tests with a beam length of 2.0 m and a span of 1.5 m. The cross sections normally had a width of 15 cm and a height of 25 cm, whereas for the beam with fractured stirrups the height was only 20 cm, as the lower section was cut off to simulate the fracture due to corrosion. The a/d ratio was held constant with a value of a/d=3.75, as well as the ratio of the longitudinal reinforcement with 2 ∅ 20 at the top and 4 ∅ 20 at the bottom. The yield strength for the reinforcement was 500 MPa for the main bars and 330 MPa for the shear reinforcement. Table 2 summarizes the properties of the 3 tests which were modelled:

Table 2. Parameters of specimen’s cross sections and material data for selected tests by [8] for the recalculation with FEM

	V1	V2	V3
cross-section height	0.25 m	0.25 m	0.20 m
shear reinforcement	-	∅ 6 / 7.5 cm	∅ 6 / 7.5 cm
percentage of straight-legged stirrups	0 %	0 %	67 %
concrete compressive strength	47.5 MPa	50.7 MPa	50.7 MPa

With regard to the finite-element-simulation of the tests, the reinforcement was modeled using beam elements and the bond behavior between reinforcement and concrete was initially considered by a simplified approach, using spring elements with a defined work law related to the bond stress slip relation of the specimen. The influence of lateral pressure was not considered for the simplified approach, but will be added when prestressed girders are considered.

The calculated shear load deflection curves can be seen in Figure 6. Since only the ultimate loads were reported in [8], a direct comparison of the curves is not possible, but the failure loads from the tests are displayed.

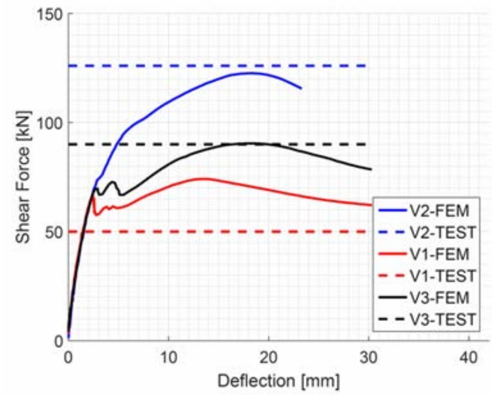

Figure 6: Numerically determined shear load deflection curves and comparison with the ultimate loads from the tests of [8]

It can be seen that the numerical models of the experiments using the finite element method show good correlation of the ultimate loads with the results from the tests, except for the specimen without shear reinforcement for which the calculated failure load was higher. In the first part before the first crack initiation, the curves are quite similar. After that, in the cracked state (state II), the shear reinforcement is activated and the behavior of the specimens clearly differs. While a transfer of forces is only partly possible for the specimen without stirrups, the shear reinforced beams can absorb the forces (which are released by the growth of shear cracks) over the crack edges more effectively. Nevertheless, the fractured shear reinforcement with straight legs is less effective. This is due to the fact, that the closed stirrups reach the yield strength over the whole length (as the ends of the vertical stirrup members are directly anchored by the horizontal parts), whereas the normal forces in the straight-legged stirrups have to build up over a certain length (see Figure 7). However, the beneficial influence of the straight-legged stirrups is clearly visible, which means that this type of shear reinforcement should be taken into account for the evaluation of the shear capacity of existing bridges.

For many existing bridges in Germany smooth reinforcing bars were used. This obviously influences the shear capacity, as the bond between stirrups and concrete is reduced, which means that the maximum normal force in the bars is reduced. This effect and also the influence of prestress on the bond behavior will be researched in the future.

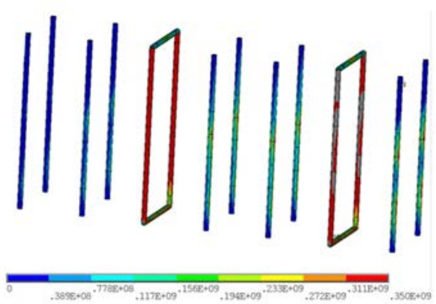

Figure 7: Stresses in the shear reinforcement (red = yield strength)

4. Outlook on experimental investigations

4.1. Testing technology and planned testing program

For the upcoming tests at TUM an innovative experimental setup was developed, which allows realistic testing of concrete beams at reduced scale using the substructure technique. Thus, an experimental investigation of bridge girders in shear and bending with realistic heights and a reduced length is possible. Hereby, the creation of arbitrary stress states can be achieved by applying loading and internal forces using external hydraulic jacks (see Figure 8).

The great advantages of this technique are that smaller loads are necessary (comparable when using symmetry conditions), easier handling and disposal is possible, material is saved and the positioning of the measuring systems is clearly defined. This makes it possible to carry out a higher number of tests. The geometry of the test specimens follows length to height ratio of approximately 3, to consider a load introduction zone according to St. Venant's principle. Arbitrary sections of the bridge girder can be analyzed using this approach. The internal forces (bending moment and shear force) are applied according to the considered section, by using 4 hydraulic jacks to apply the bending moment and 2 hydraulic jacks for the application of the shear force, which are coupled to a massive steel plate connected to the specimen. The experimental setup for the tests is shown in Figure 8.

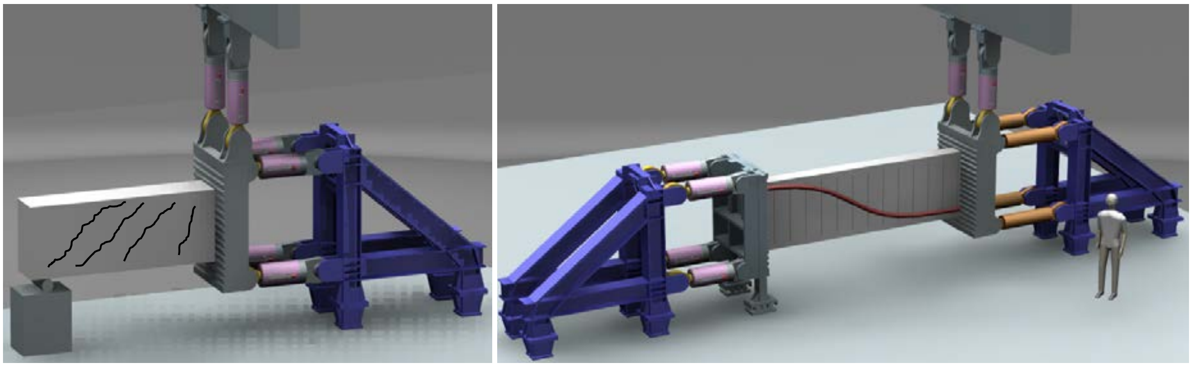

Figure 8: Experimental setup for testing of UHPFRC beams (a) and NSC bridge girders (b) in shear using the substructure technique

As the UHPFRC beams should act as single span girders, for the shear behavior only the edge region is of interest for the tests. Therefore the specimens will be simply supported on one end, whereas on the other end the internal forces are applied as explained above (see Figure 8 a). For the tests examining the influence of different stirrup types for NSC girders, the setup will be modified (see Figure 8 b), as the region close to the intermediate support of multi-span bridges is of particular interest. For this case the shear force will be actively applied on one end and the bending moment will be applied on the other end, whereas rigid rods ensure the equilibrium on the opposite ends.

Acknowledgements

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