HYBRID REINFORCEMENT MEASURES AND INNOVATIVE MEASUREMENT METHODS IN STEEL CONSTRUCTION

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Dedicated to Prof. Dr.-Ing.habil. Dieter Füg to his 80th birthday

ABSTRACT

The implementation of innovative ideas can be very efficient thanks to the intensive collaboration of different research institutions. It is important to use the expertise of the research partners, to know precisely the possibilities and limits and to create a future-oriented work schedule. In an ongoing DAAD project, this approach aims to strengthen the partnership between the authors' institutes. One objective of the project is to develop bonded reinforcements with CFRP laminates for steel construction. The focus is on fatigue-stressed constructions of steel bridges and seismic loaded structures in structural engineering. A further research focus is the application of thermovision for non-contact measurement of strains in steel components, bondlines and CFRP materials. The research is carried out within the scope of student theses, supervised by staff and doctoral students of the institutes. The sustainability of the measures used to deal with the project is essential for the success of the research project. In this way, the findings are integrated into university teaching, the knowledge gained is taught in summer schools, and young scientists are explicitly addressed.
This paper presents the general approach in the project as well as the first findings on the thermostrain method.

INTRODUCTION

In order to ensure a lasting cooperation between research and teaching institutions, targeted cooperation is essential in specialist fields. Within the framework of the ongoing DAAD-project "hybrid reinforcement measures and innovative measurement methods in steel construction", the partnership between the Chair of Steel and Timber Structures (BTU) and the Institute for Steel Construction (NTU) is to be strengthened further. Specifically, the following objectives are sought:

- Strengthening of cooperation in teaching and research
- Improving of employment opportunities for Greek graduates
- Internationalization of the research institutes

In order to achieve these objectives, a joint teaching concept for German and Greek students will be developed and the application for a research project is intended. In terms of content, the focus is on practical issues related to the upgrading of steel structures. Due to the increasing volume of traffic, the conversion of existing buildings and the prolongation of the service life, this subject presents a current problem in both Germany and Greece. The knowledge gained from the investigations is directly incorporated in the teaching at both institutes and thus contributes to a broad, future-oriented and problem-oriented education of civil engineering students. Through the exchange with the BTU, Greek students receive better professional opportunities in the European environment.

HYBRID REINFORCEMENT MEASURES

Renovation, restoration, expansion or upgrading of steel structures plays an increasingly important role in recent years. Reasons for this are growing requirements, for example by an increase of live loads, degradation of materials over time and usage and the occurrence of damage due to extraordinary events, e.g. strong earthquakes. Steel is one of the most suitable materials for such measures due to its homogeneous behaviour with a high intrinsic strength. However, using conventional reinforcement methods, as shown in Figure 1~~Figure 1~~, is not always unproblematic.

a b

Figure 1: Example for conventionally reinforcements of steel girders with a) screwed and b) welded steel plates

If, for example, steel plates are used for reinforcement, specific problems arise depending on the type of connection. In the case of screw connections, the holes cause a reduction of the cross-section, which leads to stress concentrations and results in fatigue problems. On the other hand, due to the strong heat impact during the welding procedure, residual stresses and imperfections are introduced, which in particular reduce the carrying capacity of steel members. In recent years, innovative connection techniques and materials are increasingly being investigated, which permit a more user-friendly application and avoid the above-mentioned disadvantages. An innovative joining technique that offers these possibilities is adhesive bonding. In the case of adhesive joints, the adherends are connected over the entire surface so that no stress concentrations or cross section weakening occur. The application of adhesive bonds is carried out in the cold state without the development of residual stresses or restraints.

With regard to material selection, innovative developments can be used. Inspired by concrete technology, where plastics have been used for reinforcements for years, civil engineering is nowadays experimenting with fibre materials that are bonded to steel profiles (Figure 2~~Figure 2~~). Carbon fibre reinforced polymer (CFRP) laminates are preferred, which have a high strength and insignificantly increase the construction weight. Therefore, these are hybrid reinforcement measures, where two building materials - steel and plastic - are used.

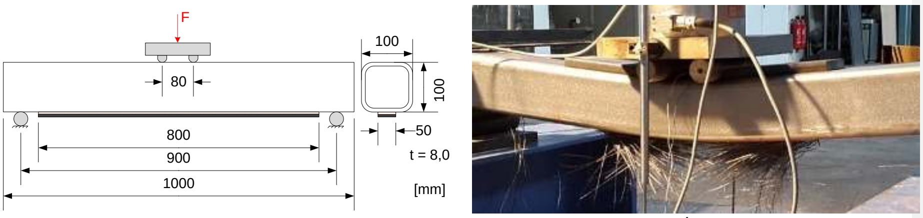

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Figure 2: a) Test setup: hybrid reinforcement made of CFRP laminate; b) failure of CFRP laminate during testing

The two institutes have a large number of investigations in this first research area. At the Chair of Steel and Timber Structures (BTU), adhesive technology has been one of the research foci for many years. In this context, reinforcements of steel structures with bonded CFRP laminates were also investigated (Bartholomé *et al.* 2014, ~~Bartholomé~~ Pasternak *et al.* 2016). Findings on fatigue behaviour of dynamically loaded steel components reinforced with CFRP strips are first obtained in an ongoing project (Ummenhofer *et al.* 2016). The NTU Institute of Steel Construction has also dealt with this topic in the context of renovations and upgrades of industrial and school buildings made of concrete

structures (Vayas *et al.* 2014). In the latest investigations, reinforcements of steel angle profiles with CFRP laminates are studied experimentally (Moragiannis 2015). Both institutes can thus profit from the cooperation and exchange their knowledge, whereby a special synergy effect is to be expected, since the experience of the BTU is so far mainly based on quasi-statically and dynamically loaded steel structures, whereas the NTU has been focused on seismic loaded concrete structures.
On the one hand, the application potential of bonded plastics for reinforcement and upgrading of steel structures is large. On the other hand, research in the field is rather sparse, especially compared to concrete construction. In the joint research project, existing gaps of knowledge will be filled by investigations on the carrying behaviour of hybrid components made of steel and bonded CFRP laminates. From a wide range of possible applications, such objects are selected, which are based on the expertise of the institutes.

Reinforcement of Lightweight Steel Construction

Due to fatigue damage or problems, many steel structures, such as road and railway bridges, cranes or even large conveyor systems, have an enormous need for restoration. In particular, the average state of railway and road bridge structures has considerably deteriorated in recent years (Bartholomé Pasternak *et al.* 20142016). Since, for economic and constructional reasons, existing structures cannot be easily replaced by new buildings, maintenance and retrofitting is indispensable. The retrofitting by the application of fibre composite materials represents an optimally suitable option with high potential in order to increase the remaining service life of existing structures. The use of CFRP laminates for cracks in sheet metal (Figure 3Figure 3a) and of so-called CFRP sheets in difficult-to-reach areas (Figure 3Figure 3b) is possible.

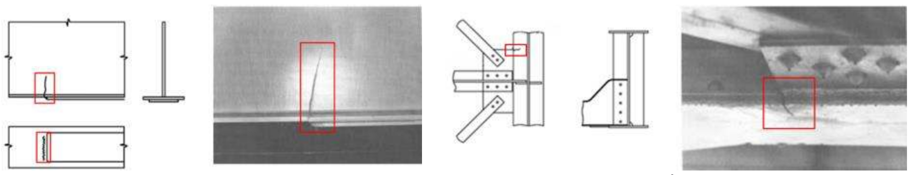

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Figure 3: a) Fatigue crack at the end of a welded steel plate; b) crack in a difficult-to-reach area of a gusset

On the one hand, the improvement methods allow the rehabilitation of cracked welds, and on the other hand the reduction as well as the prevention of crack propagation in the material of existing structures.

Reinforcement for Seismic Loading

Beam-to-column connections are the most sensitive parts of rigid frame structures in earthquake areas and the most important to ensure stability and usability. To increase the load-carrying capacity, the gussets are reinforced by the use of stiffeners. These stiffeners can be replaced by CFRP laminates in a crossed configuration, as shown in Figure 4Figure 4. A crossed arrangement is necessary, since the direction of the earthquake effects constantly changes.

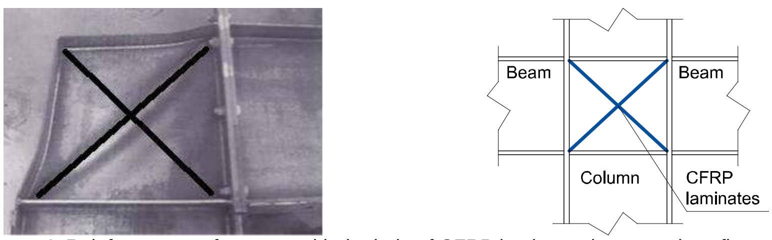
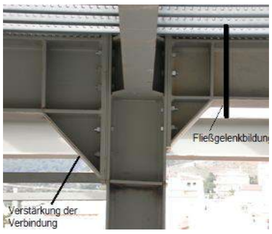


Figure 4: Reinforcement of gussets with the help of CFRP laminates in crossed configuration

Rigid steel frame structures in earthquake areas are designed in such a way that seismic energy is consumed by the development of plastic hinges. The concept of "weak beam - strong column" is used, meaning the formation of the plastic hinge takes place in the beams and not in the columns or the nodes. In the usual practice this is ensured according to Figure 5~~Figure 5~~, either by reinforcing the connection or weakening the beam ends. As an alternative, the reinforcement of the beam chords can be provided by CFRP laminates at the beam ends. The plastic deformations thus form directly at the end of the cross-section reinforcement.



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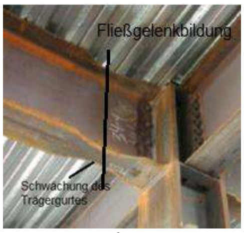

b

Figure 5: Constructive measures for the development of plastic hinges at the beam end

THERMOSTRAIN

The second research focus of the project is the application of innovative measuring techniques. The motivation for this research lies in the disadvantages and limitations of classical measurement using strain gauges. In experimental investigation of components, stresses cannot be measured directly. Instead, the strains are recorded by strain gauges and the stresses are calculated according to a material law. The disadvantages of the method include the limited local determination of the strain, the necessity of contact with the object under measurement and as a consequence thereof the disturbance of the strain field. An alternative to the strain gauge measurement is infrared thermography, which exploits the fact that during expansion the temperature of the steel changes due to energy conversion. The method known as thermostrain has been fundamentally investigated at the Chair of Steel and Timber Structures and offers the advantage of a non-contact measurement. The emitted infrared radiation of the specimen is recorded by a thermograhpic camera during the experiment so that the mentioned disadvantages of the strain gauge measurement can be avoided. The deduction of the existing stresses is drawn by means of energy conversion laws.

Both institutes are leading in Europe with regard to the application of thermography in the measurement technology of metal construction. The first developments started at BTU about fifteen years ago (Horvath 2003, Müller 2005). The temperature development of various materials under static and dynamic loads was experimentally determined and FEM-based calculations were used to deduce strains (Figure 6~~Figure 6~~).

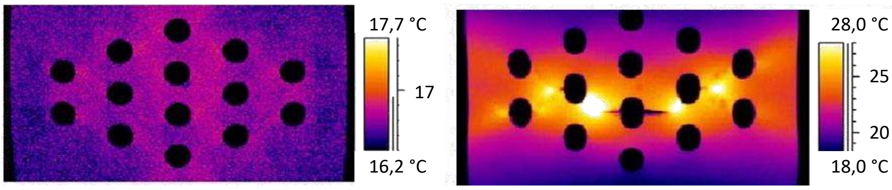

Figure 6: Temperature development of a tensile loaded specimen with holes at test beginning (left) and ending (right) (Müller 2005)

Similarly, at NTU, surveys with a thermographic camera at tests under seismic loading are carried out in order to detect the dissipative zones of earthquake-resistant constructions (Kouniaki 2015).

Therefore, a complementary synergy effect can be developed in the field of measurement technology, so that both institutes can benefit from the knowledge and experience of the partners.

Principle of Thermostrain Method

The thermostrain method is an innovative measuring technique in which the material stress on flat structural components under varying loads can be measured visually and without contact. In contrast to the common techniques, e.g. strain gauges, this method measures the heat radiation of the stressed component instead of the deformation. The heat radiation is scanned with a high-resolution infrared camera and converted into a corresponding false colour image as shown in Figure 7. From the registered temperature changes a deformation state of the specimen can be deduced. This is done with the help of a determined specific thermo-mechanical correlation of the material taking into account thermodynamic laws.

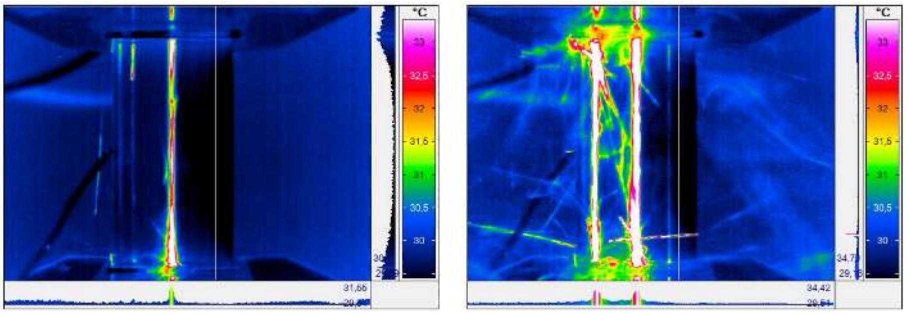

Figure 7: False colour images of tensile-stressed carbon fibre reinforced polymer lamella during failure

Experimental Investigation on CFRP Laminates

In the framework of a bachelor thesis at BTU the application of the thermostrain method for fibre reinforced polymer laminates is being investigated. Therefore eight identical specimens with the dimensions 250 mm x 80 mm x 1.2 mm (length x width x thickness) were prepared and tested in tensile tests.


Figure 8: Specimen (left) and prepared specimens (right)

The specimens were clamped in a 500 kN tensile testing machine and a 'VarioCAM® high resolution' thermal imaging camera was placed at a distance of about 50 cm in front of the specimen. To measure the displacement of the specimen a tensometer was fixed on the side facing away from the camera to avoid disturbance of the thermal image. Additionally a film camera was placed to the side of the thermal imaging camera to record the whole process. A felt mat was positioned behind the specimen to increase the contrast and to enable the camera to focus the specimen.

The test velocity was varied for the test series. The objective was to determine the influence of the test speed on the mechanical or/and thermal behaviour of the CFRP laminate. Due to the polymer specific properties of the CFRP matrix a dependency of the temperature development on the test velocity could be registered. For the first three specimens a testing speed of 5 mm/min was used, as recommended in DIN EN ISO 527-4 for the quality control of CFRP laminates. Specimens 04-06 and 07-08 were tested with a testing speed of 2.5 mm/min and 10 mm/min respectively (see table 1). The tests were conducted under approximately constant climate conditions, with an air temperature 28° C and a relative humidity of 70 %.

Table 1: Test velocity and recording frequency of data

Specimen	Test velocity [mm/min]	Recording frequency of data [Hz]
01-03	5,0	25
04-06	2,5	25
07-09	10,0	50

The results of the experiments are summarized in a stress-strain-diagram shown in Figure 9. It can be seen that the CFRP material shows linear-elastic behaviour. During the test the elastic deformation leads to a slight temperature reduction, which is known as the thermo-elastic effect. The thermo-elastic effect is followed by a noticeable warming (0.5-0.6 K) at the clamping jaws (Figure 10). An enormous thermal energy release can be observed when the specimen fails (see Figure 7 right).

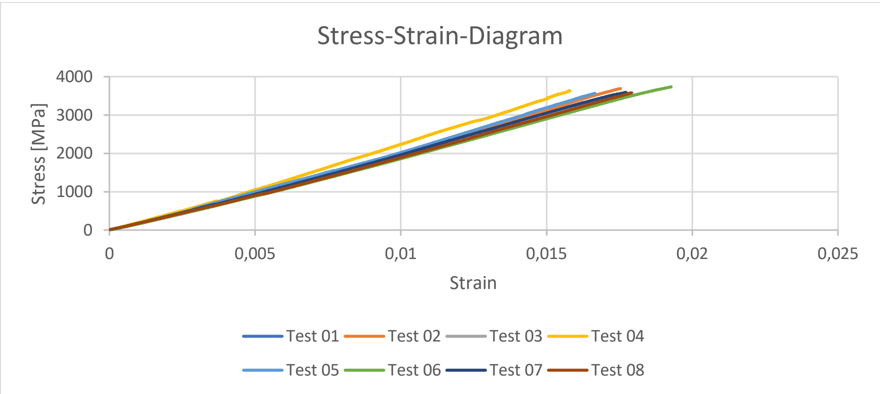

Figure 9: Stress-strain-diagram of the test series

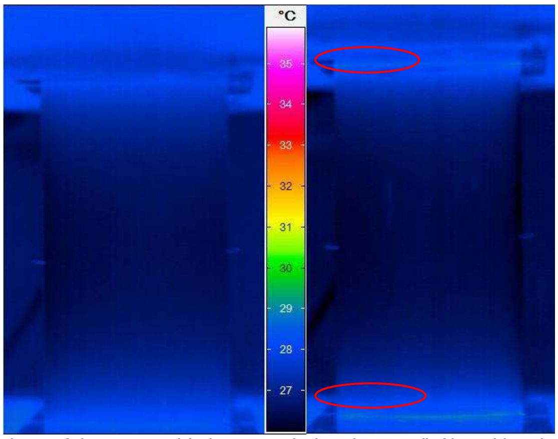

Figure 10: Comparison of thermographic images: during the test (left) and just before failure (right)

The characteristic heating of the CFRP laminate surface near the clamping jaws (Figure 10 right) could be an indicator for the failure of the specimen. Thus the thermostrain method could be used to predict the failure of CFRP elements due to stress concentrations. It is assumed that the observed behaviour results from transverse contraction effects at the clamping jaws.

Future investigation will show whether the registered energy conversion results from starting of fibre failure or other phenomena. Thus the following research in this field will focus on the influence of the test setup for the application of the thermostrain method. On the one hand the geometry of the clamping jaws should be investigated more deeply. As shown in Figure 11 the clamping area of the machine consists of jaws and an inclined plane. This mentioned geometry (angle of the plane) leads to an increasing horizontal pressure while increasing the vertical force. Thus stress concentrations at the claiming support are introduced. On the other hand friction effects at this critical point should be evaluated in more detail.

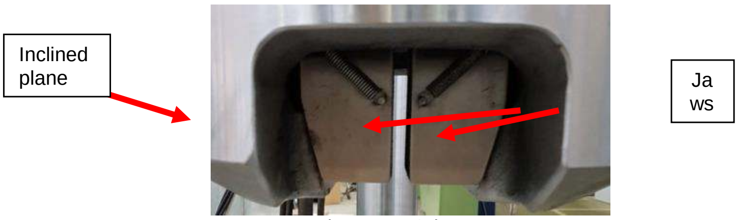

Figure 11: Grip-setup

In order to deduce a relation between the measured mechanical and thermal properties a numerical simulation using the general-purpose-software ABAQUS/CAE was carried out. The created model was simplified without considering plastic effects or stress redistribution due to the failure of single fibres, so as to be manageable as a student project. The results in Figure 12 for the stresses in longitudinal and transversal direction indicate a stress concentration at the supports. This distribution is in accordance with the observed behaviour in the experiments, more specifically in the thermal images. In the longitudinal direction the stresses are concentrated at the specimen corners.

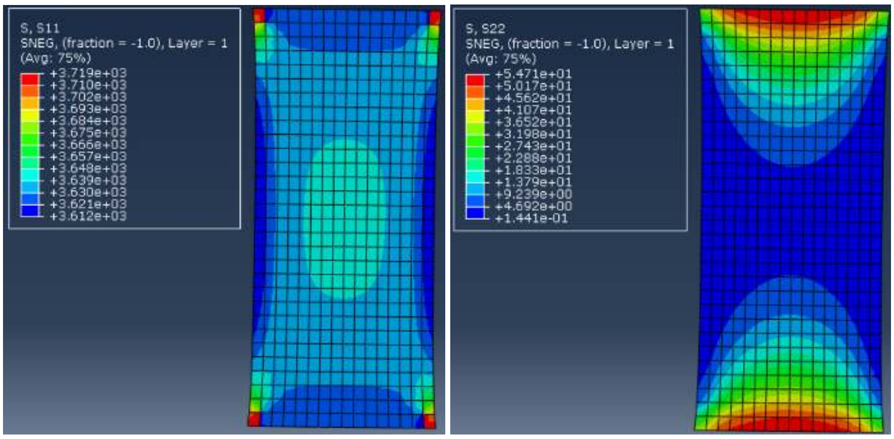

Figure 12: Stresses in longitudinal (left) and transverse direction (right)

The presented investigation should be understood as preliminary work to indicate the applicability of the thermostrain method for CFRP materials. Following conclusion can be drawn from the experimental and numerical findings:

- During testing a slight surface temperature variation was observed. Thus it is of major importance to guarantee constant environmental conditions (temperature, humidity). The failure occurs with a high energy release, which can be registered as a significant temperature change with the help of a thermal imaging camera.

- Stress concentrations at the clamping jaws result from transverse contraction effects and lead to an energy release.
- To avoid a failure due to stress peaks, weakening of the specimen cross section in the middle of the longitudinal direction is recommended.
- A suitable numerical model should include the classical laminate theory as well as redistribution effects between single fibres due to the matrix compound.

IMPROVEMENT OF ACADEMIC COOPERATION

In addition to the specialist knowledge, the DAAD project aims above all at an improvement in the academic partnership between Greek and German universities. The project is designed in such a way that the common creation of teaching events and the supervision of master or bachelor theses as well as diploma theses is done in cooperation. Within the framework of student theses numerical investigations are carried out at the BTU for quasi-static and at the NTU for seismic loading. One or two master's or diploma theses per year, are aspired to at each institute and supervised by scientific staff or doctoral students.

At each institute, experimental investigations on component specimens are carried out for selected reinforcement measures. The strain measurement is realized by thermostrain due to the above-mentioned reasons. The aim of the tests is to calibrate the numerical models as well as the combination of temperatures and strains/stresses of the materials used and thus the expansion of the existing knowledge on CFRP-reinforced steel components. These studies are implemented as part of student work and are supervised by Greek and German staff. Joint teaching sessions are held at the BTU and the NTU. This requires the specific definition of the contents of teaching in close cooperation, which also strengthens the partnership at academic staff level. Such coordinated teaching program can also be transferred across the project to other content or used for future lectures and adopted in general academic courses.

The findings of the examinations will be presented to students and interested employees within two summer schools in the years 2018 and 2019, thereby enabling the participants to plan, evaluate and design reinforcement measures for steel structures. The know-how gained can be regarded as a unique feature, since the adhesive technology as well as the thermostrain method is not part of general university courses in civil engineering. The graduates of the Summer School thus receive a broader education compared to international standards, which means a benefit for future employment opportunities, especially for Greek university graduates. In addition to the international contacts, students receive an additional scientific and technical qualification by exchanging with the partner institution, since the contents are experimental-oriented. Thus, a link between teaching and research takes place, which increases the career opportunities of the graduates in research facilities.

SUSTAINABILITY OF MEASURES

The approach in the project is designed in such a way that sustainable results are to be expected. On the one hand, the professional subjects of the theses and summer schools are oriented towards future problems of civil engineering. As a result of the increase in loads and increasing service life of steel structures, reinforcement measures and, in the future, rehabilitation and retrofitting measures are required (Bartholomé *et al.* 2014). The design of such methods is the content of the investigations.

On the other hand, young scientists and students are explicitly addressed with the project. In this way network relations with a thematic focus will be created, which can be actively used for future tasks. It is also planned to continue the cooperation on content in the field of research on follow-up projects.

CONCLUSIONS AND FUTURE WORK

The bonding technology has the potential to efficiently design reinforcements of existing buildings in steel construction. In this case, the bondlines can be designed in such a way that a quasi-rigid compound is realized and thus the load bearing capacities as well as the stiffness of components are

increased. Various applications, for example for the rehabilitation of steel bridges, are analyzed and evaluated within the framework of the presented project. A further possibility consists in utilizing the energy dissipation capacity of elastic bondlines for the earthquake-resistant design of steel structures. Initial research on this methodology will be pursued for student theses in 2018. The applicability of the time-temperature superposition principle of selected adhesives will be considered. By means of experimental investigations, the frequency-dependent carrier behaviour of bondlines will be determined. In final master's or diploma theses in 2019, large-scale test specimens are to be experimentally studied and numerically modelled. The objective is to develop a suitable design for steel reinforcements in bridge construction as well as the earthquake-proof design of reinforcements in structural engineering. The gained knowledge will be given to all interested students and engineers within two multi-day summer schools 2018 in Athens and 2019 in Cottbus.
In addition to the scientific advance, the students and employees involved in the project benefit from the intensive exchange and the improvement of linguistic and cultural skills. In particular, Greek graduates will be given the opportunity to make contacts in Germany and thus gain a better employment perspective in the profession of civil engineering. The background is the strongly negative impact of the current economic crisis on the construction sector in Greece.

ACKNOWLEDGEMENT

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