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Value of health monitoring in structural performance assessment using digital image correlation systems

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Abstract

In engineering, quality control (QC) is related to systems development in order to ensure that products or services meet or exceed expectations and needs. Today, it is a challenge to manage infrastructures in an efficient manner. Thus, there is an increasing need to develop strategies to ensure asset quality with the aim of reducing the risk of unexpected costs. In order to assure the desired service quality, with minimum interruptions, maintenance actions are taken when the risk of service impairment, interruption or losses in life cycle costs reach predefined levels. This risk depends on the establishment of performance goals for components, which when compared with performance indicators, obtained from visual inspection techniques, non-destructive tests or by monitoring systems, provide information regarding the assessed asset condition. The objective of this paper is to analyse a digital image correlation system and its ability to assess performance indicators, such as crack patterns, crack openings and vertical and horizontal deformations. The obtained values are then compared to goals so that structural performance assessment strategies can be implemented in an efficient and sustainable way. In particular, the digital image correlation system is used to obtain valuable information about the shear transfer mechanisms from reinforced concrete beams. This contribution focuses on pre-stressed pre-cast beams that are loaded in shear following a certain sequence of loading and unloading cycles before the load is ultimately increasing until failure. Obtained results include a load-dependent photogrammetric documentation of crack patterns, a continuous quantification of crack openings, and an accurate measurement of vertical and horizontal deformations. These findings are basic elements for the enhancement and assessment of existing analytical formulations.

Keywords: Click here to enter keywords. Each keywords should be separated by semicolon. No more than 5 keywords allowed.

Introduction

In engineering, quality control (QC) is related to systems development in order to ensure that products or services meet or exceed expectations and needs. Today, it is a challenge to manage infrastructures in an efficient manner. Thus, there is an increasing need to develop strategies to ensure asset quality with the aim of reducing the risk of unexpected costs. In order to assure the desired service quality, with minimum interruptions, maintenance actions are taken when the risk of service impairment, interruption or losses in life cycle costs reach predefined levels. This risk depends on the establishment of performance goals for components, which when compared with performance indicators, obtained from visual inspection techniques, non-destructive tests or by monitoring systems, provide information regarding the assessed asset condition.

Independently of the type of structural health monitoring system implemented, the general purpose is to efficiently monitor the structural performance such that proper maintenance actions may be identified and implemented in a timely fashion, with the aim of ensuring appropriate safety levels, maintaining the quality of the environment, as well as minimizing the asset lifecycle costs. In this paper a digital image correlation system is used to assess performance indicators, such as crack patterns, crack openings and vertical and horizontal deformations. The obtained values are then compared to goals so that structural performance assessment strategies can be implemented in an efficient and sustainable way.

This research has been significantly affected by the objectives of COST TU1406 as well as the objectives of the COST TU 1402. The main objective of Cost Action TU1402 is to facilitate sustainable societal developments through improvements of resource efficiency, productivity, robustness, reliability and safety in the design and asset management for structures and infrastructure systems by optimized SHM systems. The Value of Information analysis quantifies this benefit relative to the costs of collecting the information. Hence, the identification of optimal SHM strategies is facilitated for both new and existing structures under a range of operating conditions and constraints. Hence the objective of TU1402 is to quantify and assess the Value of Information collected by SHM in a life-cycle perspective prior to its implementation. Most often the beneficial value of SHM is only implicitly assumed, without considering how the information shall be utilized for improving the decision basis for optimal life-cycle management of the structures. Information is only valuable if it deals with measurable and quantifiable parameters that may help decision making in asset management. Normally, the parameters/variables used in infrastructure management are defined as performance indicators. Follow-up of the performance indicators along service life and their comparison with predefined target values according to desired performance goals will allow the definition of quality control plans. Therefore, the assessment of the value of information provided by the SHM techniques in regard to a set of predefined performance indicators is the key issue in a sustainable life-cycle assessment of infrastructures.

The shear-bearing capacity of reinforced concrete structures plays an important role concerning the sustainable life-cycle assessment of infrastructures. In the last decades, these structures had been designed on different safety formats and levels, which in some cases do not comply completely with the load models occurring today. Hence, the owners and operators of such infrastructures and structures are highly interested in the assessment of the real existing shear load capacity and the still possible increase in the shear loading using advanced health monitoring or testing methods. For that kind of assessment of existing structures the value of health monitoring in structural performance assessment is obvious. The strength of reinforced concrete beams subjected to combined shear and flexure is affected by complex phenomena, such as existing multi-axial states of stresses, the anisotropy induced by the diagonal concrete cracking, the interaction between concrete and reinforcement and the brittleness of the failure mode. Trying to obtain valuable information about the shear transfer mechanisms, a large number of shear tests have been performed during the last 60 years, as summarized in Collins et al. (2008). Currently, both in the US and in Europe the shear design provisions are undergoing a revision. Open questions concern, among others, the existence and magnitude of the size-effect, see Yu et al. (2016), the influence of reinforcement degree and pre-stress level. Many different model formulations either mostly empirical, based on different physical mechanisms, see Mari et al. (2014)., or supported by fracture mechanics have been proposed. Yet, clear evidence and quantification of the contribution of certain mechanisms can only indirectly be obtained by inverse statistical analysis.

This paper attempts to shed some light on the relevance of different mechanisms utilizing digital image correlation. Widely used performance indicators such as the crack pattern and crack width are considered. The SHM technique the added value of which will be investigated is the recently proposed Digital Image Correlation (DIC) methodology. Its applicability on the crack pattern recognition and quantification of crack width is investigated in a case study dealing with the response to combined shear and bending of a reinforced concrete structure. The methodology then is applied on 4 pre-stressed pre-cast beams that are loaded in shear following a certain sequence of loading and unloading cycles before the load is ultimately increasing until failure. Obtained results include a load-dependent photogrammetric documentation of crack patterns, a continuous quantification of crack openings, and an accurate measurement of vertical and horizontal deformations.

Shear models for reinforced beams

For an efficient value of health monitoring in structural performance assessment it is of great importance to understand the physical mechanisms and models of the process that should be analyzed, for instance such as the fracture process due to shear loading. Therefore it has been considered as very important to process first a literature and research survey of essential shear capacity models before starting with the definition of performance indicators, goals and processes. Some of these results are follows: Refined theoretical models have been developed by Bairan & Mari (2006) which are capable of tracing the non-linear response of these structures, but are too expensive and time consuming for daily engineering practice and design. Thus, simple semi empirically based equations have been also developed, some of which have been adopted by design codes European Committee for Standardization (CEN). (2002), although their applicability might be limited to the range of experiments used to derive them. Consequently, in some cases, the scatter of the predictions when compared with the experimental results is too large. Furthermore, recent studies Sagaseta & Vollum (2011) reported that EC-2 overestimates or underestimates the shear strength, depending on the type of aggregate or the type of cross section, and neglect some key contributions. These facts suggest that there is still no universally accepted simplified mechanical model for shear design of reinforced concrete (RC) members, especially without shear reinforcement. In addition, when assessing existing structures, they may falsely be considered unsafe. Recently, it was demonstrated how adequate filament non-linear models with shear capabilities are suitable for assessing this type of cases Ferreira et al. (2013). Although adequate numerical models are a valuable assessment tool for existing structures, it is of paramount importance to develop rational mechanical models capable of reproducing as accurately as possible the physical behavior of concrete structures in order to safely and economically assess existing structures. Furthermore, these models allow, after some simplifications, deriving simple equations which are suitable for code provisions or for their use in daily engineering practice. Among them are the Tooth model developed by Reineck (1991), simplified models based on the Modified Compression Field Theory, Vecchio & Collins (1986), the Critical Shear Crack theory Muttoni & Ruiz (2008), the Splitting Test Analogy Desai (2004) and the theories based on the shear resisted by the uncracked compression chord Choi et al. (2007). On the other hand, methods based entirely on the theory of plasticity have also been applied with good results.

The above models were developed from different approaches, emphasizing the contribution of different shear transfer actions and proposing different expressions with different governing parameters. Nevertheless, their strength predictions are similar and fit generally well with the experimental results. This fact suggests that beyond possible adjustments of factors to fit experimental results, a reason for this coincidence is that successive mechanisms are activated as the load level increases and the structure becomes damaged, so that when equilibrium in a region is no longer possible with a governing shear transfer action, another action is activated. These redistributions of stresses may occur suddenly, given the brittle nature of cracking, but in some cases may produce small changes in the resultant internal forces, so that similar ultimate shear-flexural capacity can be obtained from different approaches.

This comprehensive survey allowed the identification of performance indicators based on the COST TU1406 and TU 1402 philosophy for the following shear capacity dominating components and its processes, see also Huber 2016

- shear force transmission due to crack interlocking
- shear force capacity due to dowel effects of reinforcement layout
- shear force transmission due to cracks across tension forces
- shear force capacity due to activated compression region
- shear force capacity due to the shear reinforcement
- shear force capacity due vertical component of pre-stressing forces

The surveys and the experiments and non-linear modeling indicated that the above-described dominating components and its processes starting and pronounced differently associated with the load levels can be characterized perfectly by the crack pattern development.

It is obvious to choose a monitoring system like the Digital Image Correlation system, which focuses on the crack pattern development. Furthermore, it was of great interest in which form the development of the crack pattern can be transferred to the strain state of the reinforcement during the whole loading process, which was an additional objective in this research.

Basics about the tested R and T beams

As already mentioned before, a major objective of this research was the analysis of advanced monitoring systems for the assessment of shear and flexure performance of pre-stressed reinforced concrete beams and its evaluation with regard to its value for health monitoring. The assessment has been based on using information from (a) various monitoring systems, (b) experimental component testing, and (c) information from code based destructive test methods on large-scale samples. There is also a keen interest, whether the adjusted non-linear FEM models can capture geometric and material size effects.

The concrete and reinforcement layout of the laboratory tested 5:00 m long T and rectangular shaped beams have been derived from the shear bearing properties of a pre-stress 33.00 m TT concrete lightweight roof elements. It was of particular interest to have the same multi-axial states of stress and the interaction between concrete and reinforcement (bond) in the shear field area of beams, the full scale and the laboratory scaled. The laboratory beam set up has further been differentiated into (a) none, 50% and 100% pre-stressed elements in order to elaborate the effect of the normal force on the shear performance and capacity of the beams and to allow a validation of existing analytical formulations, and (b) in beams with web heights of 30, 45 and 60 cm in order to capture possible geometrical and material size effects on the shear performance. The three TT lightweight roof elements are characterized by a web width of 14 cm and a height of 60 cm in the support lines and 90 cm in the centre line of the beams. The web connecting slabs are characterized by a thickness of 12cm and a width of 300cm. The twelve experimentally tested T or rectangular shaped beam elements are characterized by a web width of 14 cm and heights of 30, 45 and 60 cm along the whole length and slab thickness of 8 cm and a width of 150 cm. The twelve scaled beams served for the comprehensive updating procedure of the non-linear numerical FE model with respect to the shear bearing performance.

The fracture mechanical concrete properties are essential for the development of non -linear finite element models and the evaluation of shear capacity models. Therefore, in this project 160 concrete conformity test specimens had been casted in parallel to the casting of the four laboratory tested beams in order to obtain (a) the concrete compressive strength f_c, the concrete tensile strength f_{ct}, the concrete young modulus E_c, and the total fracture energy G_f, at a curing time of 7, 28, 56 and 125 days from at least 7 samples, and (b) to perform the conformity tests at an age of 28 days and the time of the testing of the laboratory beams. More details regarding the casting and testing procedures are shown in Krug (2017). These tests on the large number of concrete conformity test specimens yield a high number of time-varying data for $f_c(t)$, $f_{ct}(t)$, $E_c(t)$, and $G_f(t)$ which are partly sometimes more and less correlated in the timeline. These information is important for the shear performance assessment process based on analytical formulations, the interpretation of experimental results as obtained for the 12 tested laboratory beams, and are very important for the complex up-dating process of non-linear modeling. However, it requires the definition of a reference data set to which the high number of varying data can be related and efficient used in the updating of models. Details regarding the creation of a reference system are shown in Krug (2016)

Testing and classical monitoring

Figure 1 shows schematically the overall test setup. The length L of all laboratory tested beams was 5 m and the effective span l_{eff} was 4,75 m. The distance a between load point and support varied between 0,97 m and 1,89 m in order to have an appropriate shear span-to-depth ratio a/d to avoid un-favourable effects on shear load transfer and bond shear failure. Typically, in shear tests the instrumentation is focusing first of all on the identification and monitoring of the compression field and the crack formation. Hence arrangements are the application of strain gauges (SG) glued externally along the sides of the concrete cross section, internal strain gauges fixed to the reinforcement and displacement transducers (e.g. LVDTs), Krug (2016). In the present study, all these types of different electrical sensors were used. The external strain gauges were applied to the side surface of the web partly in a rosette-like arrangement in order to derive the principal strains and its inclination (see Figure 2). Internal strain gauges were glued on additionally cast-in reinforcing bars with small diameters (ϕ_s = 6 mm). They were situated mainly at the same x/z-position like the outside ones in order to allow for later correlation studies between outside and inside recorded data. The LVDTs attached to the web are inclined perpendicular to the expected shear crack to make them more sensitive to shear crack openings but less to bending cracks, (Stoertzl 2015). In addition, LVDTs or laser sensors were used for vertical deflection measurements at the bottom of the beam. Moreover, visual inspections and manual crack recordings and crack width measurements by means of crack magnifiers were processed.

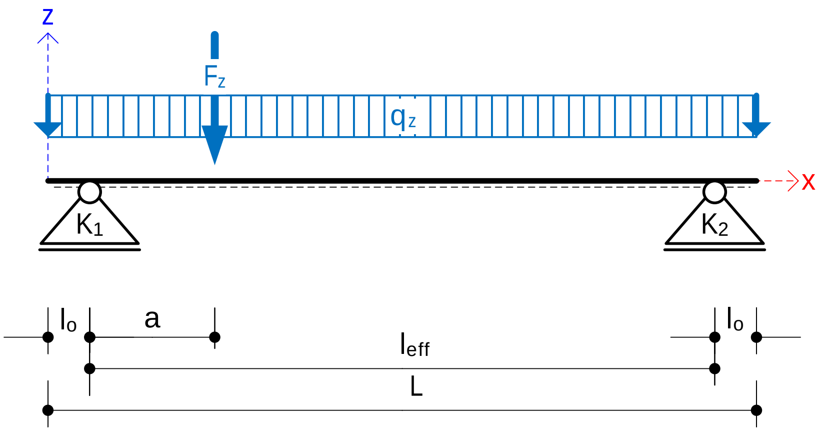


Figure 1.: Overall test setup

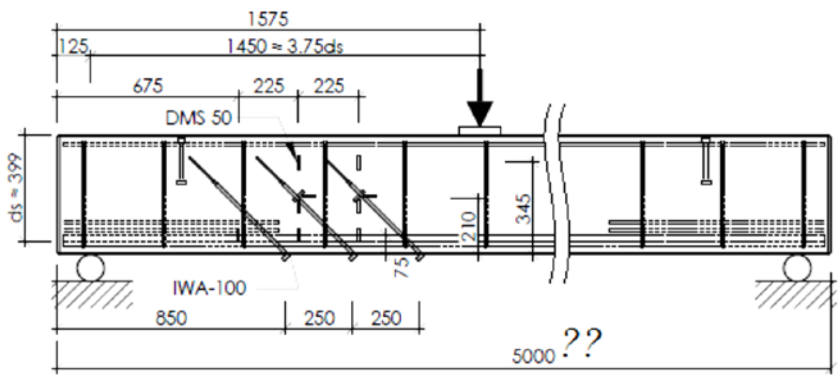


Figure 2.: Side view of measuring instrumentation

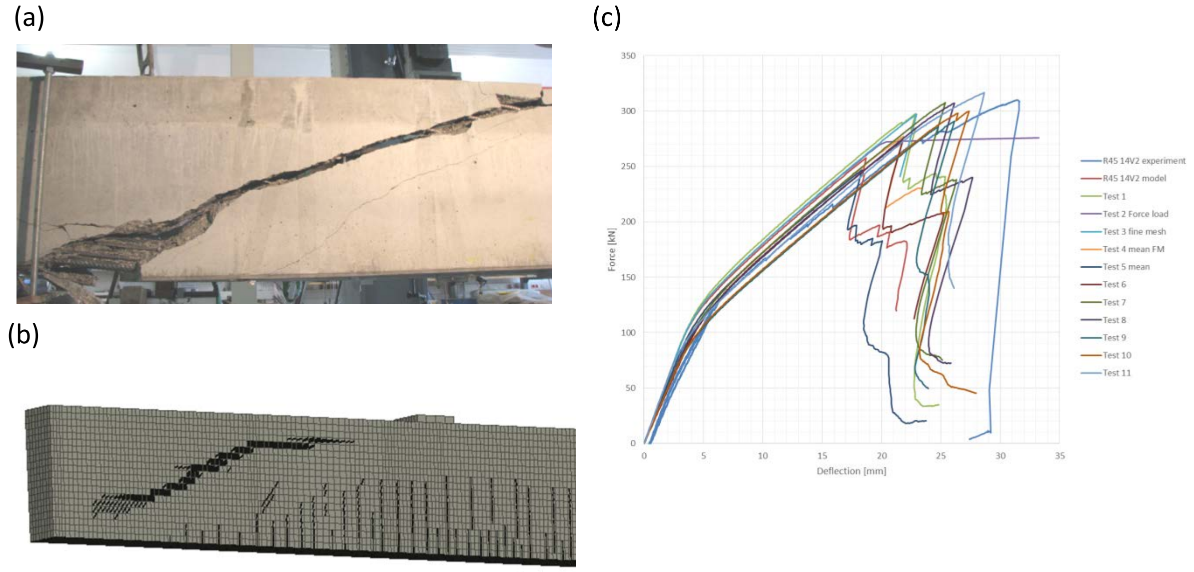


Figure 3.: Experimental tested and modelled beams R30 (a)the shear crack pattern at the load capacity, (b) the associated crack pattern of the optimized nonlinear Finite Element model, and (c) the modelled vs experimental tested force-deflection curve.

All of the rectangular (R) and T-shaped Beams were tested under static loading in a three-point bending setup. To simulate shortly the life-cycle, first of all the specimens were subjected to a pre-loading phase consisting of three load cycles up to a representative SLS-load level estimated in advance. When reaching the upper SLS load level, the crack propagation was recorded by the above mentioned visual inspection. Afterwards the load was increased in displacement-control until failure. Figure 3 depicts (a) the shear crack pattern at the load capacity,

(b) the associated crack pattern of the optimized nonlinear Finite Element model, and (c) the modelled vs experimentally tested force-deflection curve. Furthermore, this figure shows that the difference in maximum load and stiffness is rather negligible.

Values of Digital Image Correlation useful for health monitoring and performance assessment

Digital Image Correlation is a non-contact optical technique used for measuring strain and displacement. The system is based on grey scale value digital images. Using a stereoscopic sensor set-up each object point is projected on a specific pixel in the image plane of the respective sensor. Knowing the imaging parameter for each sensor (intrinsic parameter (reference) and the orientation of the sensors with respect to each other the position of each object point in three dimensions can be calculated. In order define the absolute size of the object a reference length is required and usually introduced curing the camera calibration. Using a stochastic intensity pattern (speckle) on the object surface, the position of each object point in the two images can be identified by applying a correlation algorithm. The displacement and deformation of each point that compose the speckle allows the program to compute the displacement and the strain field. Applied to civil engineering problems, this technique not only allows the determination of deflections, the axial shortening of structural members and local strains but also crack patterns indicated by displacement jumps. As previously introduced, the beams are sustained by two supports and loaded eccentrically to ultimately cause shear failure. The accuracy and especially resolution of digital image correlation (DIC) is related to the pixel density of the camera, the size of the area of interest (AOI), and the quality of the speckle. A comprehensive discussion of the theoretical background and the applied algorithms can be found in Sutton et al. 2009. The latter is determined by the ratio between characteristic size of the stochastic pattern and pixel size. Taking into consideration that the interesting zone is the one where the shear cracks will develop (Zone a of Fig. 1) the investigation is focused on this area. In the next phase the "ideal" camera setup has to be chosen. Variables are the distance between object and camera, depending on the lens and chip, the orientation of the cameras and the angle between the cameras of a stereo pair or the intentional choice to go for individual 2D single camera systems to cover a larger area of interest. This choice is driven by the magnitude and type of the expected deformations as well as the likelihood of significant out-of plane deformations. For the present problem, considering that four 9 Megapixel cameras were available, two options have been considered:

- The first option was using two 3D systems (each 3D system is composed of two cameras) set in such a way that a sufficient overlap between the two areas of interest is ensured, allowing both so far independent systems to be linked by coordinate transformation.
- The second option is to use separately the 4 cameras in order to make use of all the available resolution by moving the cameras closer to the beams and avoiding any overlap.

Both approaches have advantages and disadvantages. In this study four independent 2D systems (single camera) have been chosen for the following reason:

- the out of plane component is considered negligible compared to the in-plane components.
- four independent 2D systems allow a substantially higher on specimen resolution which improves the ability to detect small cracks and quantify crack openings.
- The associated higher error due to lens distortion and out of plane deformations is considered acceptable in light of the goal to measure (a) global deformations such as deflections, and (b) perform a full field documentation of the crack development.
- The effect of out of plane deformations can be reduced by a perfectly level and centred setup of the cameras, as chosen for this study.

A crucial step is the specimen preparation, namely the creation of the stochastic pattern. In order to optimize the quality of the analysis it is important to ensure a "perfect" contrast in the images. This can be achieved by painting the beams white before applying the speckle in black. The speckle was applied with an airbrush in order to have the most repeatable and controlled speckle size. Furthermore, it is essential to avoid shadows and reflections by using non-gloss color, covering all reflective surfaces and setting a number of light sources equipped with diffusors.

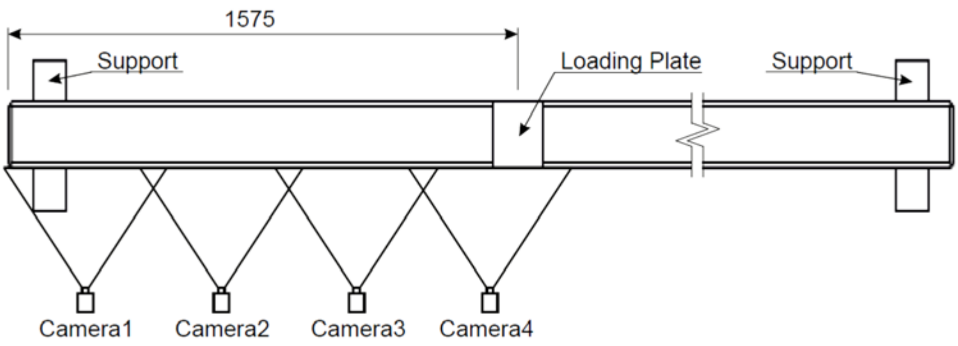


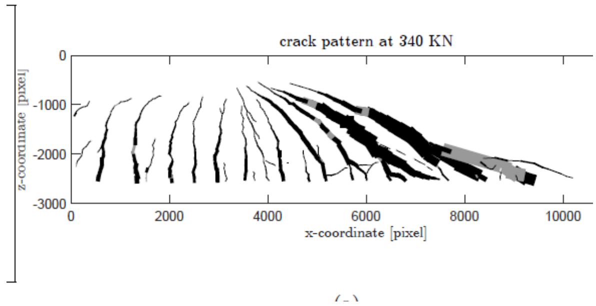
Figure 4.: Sketch of the Digital Image Correlation set-up

Correlating a set of images with the initial set provides information about the deformation state, and by derivation, about the strain field. The crack pattern then can be automatically determined based on the first principal strain field. The correlation analysis itself basically has only one parameter – the subset size. Like a moving average filter, a square correlation matrix is pushed over the image to mathematically express the local change between two pictures related to deformations. Not unlike a finite element software, in case of a large subset size (element size) average strains with the smeared effect of cracks are determined. This approach is suitable for the measurement of global deformations, e.g. a bending line.

Here the task at hand is the determination of crack patterns and their evolution in time. Consequently, a small subset size is chosen allowing a good crack detection at the cost of higher noise in the output due to local variations in the speckle pattern, and of course, significantly higher computational costs. Even though the first principal strain field is suitable to localize cracks it has to be noted that a strain field is a bad choice to quantify the crack opening. Depending on the subset size the actual crack (=displacement jump) is always smeared over a certain length resulting in ambiguous readings. Furthermore, if the crack opening exceeds a certain percentage of the subset size, correlation is locally lost, messing with automatic algorithms.

Thus, here we propose a semi-automatic crack pattern survey with the following steps: (1) determine principal strain field with small subset size; (2) trace cracks based on fully developed crack pattern; (3) extract automatically the actual displacement jump along the traced lines for all time steps by e.g. Matlab script; (4) project the displacement jump onto the line segment to determine crack opening w90 and crack slip w00. A further output is the crack inclination α measured between line segment and vertical axis, measured clockwise.

In Figure 5 a typical crack pattern for a load level of 340 kN (Beam R30 50% pre-stressed) as obtained by the semi-automatic procedure is presented. The line width scales with the crack opening. Grey segments are interpolated for neighbouring segments. A pixel corresponds to 0.18 mm.



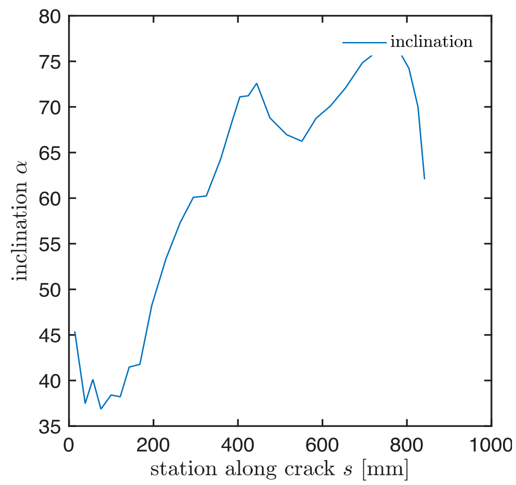


Figure 5.: Crack pattern development

Figure 6.: Crack inclination α along station s for a typical shear crack

For each of the line traces the geometrical information, i.e. the evolution of inclination, can be plotted against the station *s* along the crack where *s* = 0 represents the one end of the fully developed crack, for bending cracks equal to its initiation on the surface, see Figure 6. In Figure 7 the evolution of both components of the crack – opening and slip –with load level and depending on the position along the crack is presented. At 91 kN a small bending crack with a maximum opening of 0.05 mm is present. This crack quickly grows into a shear crack. It is interesting to note that the opening seems to be constrained until *s* = 100 mm, corresponding to the position of the tendon. Furthermore, a distinct shear slip is present in the range 0 < *s* < 300 mm.

(a) (b)

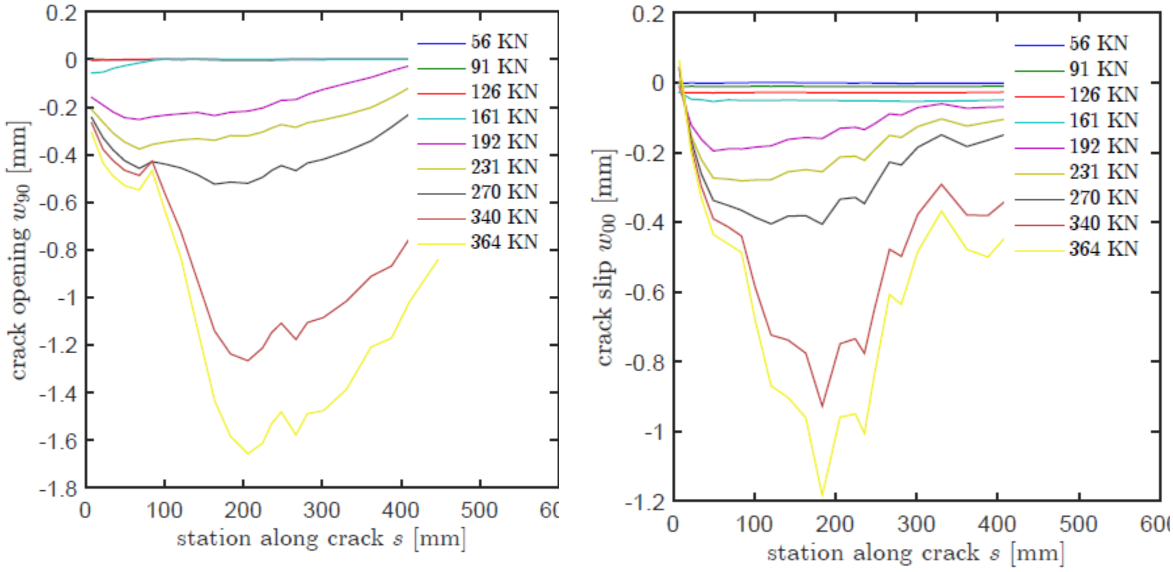


Figure 7.: Crack pattern properties (a) opening, (b) slip

Fig. 8 presents the comparison between DIC strains and the corresponding electrical strain gauges on the reinforcing bars (Slowik et al. (2015)). The graphs show that some of the strains derived from the DIC measurements on the surface of the beams show a good agreement with strains measured on the reinforcement (Fig. 8 (a)) and some are significant deviating (Figure 8 (b)) due to crack formation.

(b)

(a)

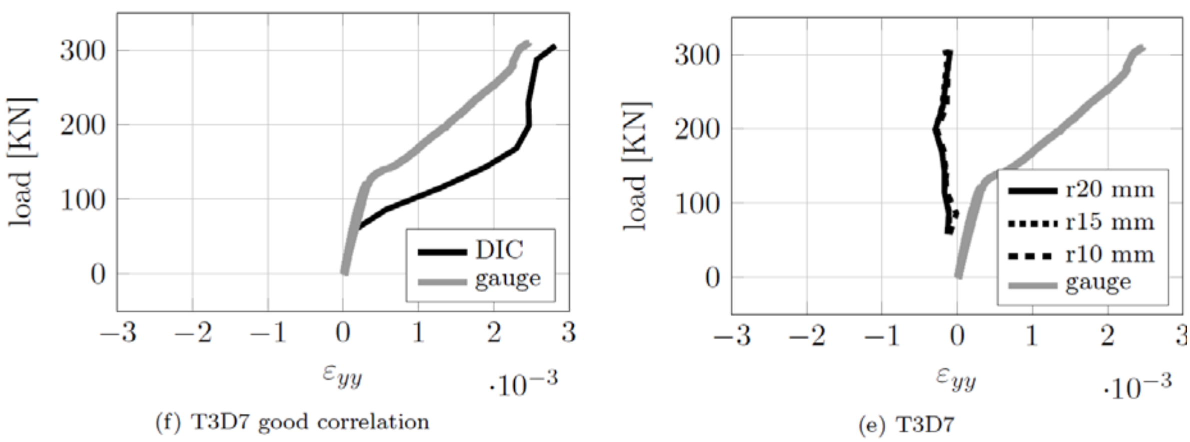


Figure 8.: Strain measurements horizontal ε_{xx}

Conclusions

Based on the performed investigation and case-study of four prestressed beams loaded in shear the following conclusions regarding the added value of digital image correlation (DIC) for structural monitoring and the derivation of performance indicators can be formulated:

- The first studies on the digital image correlation systems, which also provide important insights for TU 1402, demonstrate the capability of the method in the recording and interpretation of the crack pattern development in the shear field zone during the loading process up to the shear bearing capacity. The technology also shows a high potential for the understanding and interpretation of complex mechanical processes of the shear behaviour of reinforced concrete.
- A first comparison of the DIC recorded surface strains with the strains on the embedded reinforcement demonstrate partly a good agreement and, hence, the possibility to map surface measurements to the flow of internal forces and the activation of specific reinforcement elements.
- The full strain and displacement field obtained through DIC monitoring offer grate potential for the optimization of monitoring systems. A short-term DIC monitoring campaign could offer the basis for the design of a cost-efficient long-term monitoring system using few traditional sensors placed at critical or highly sensitive sections.
- On top of the direct value of DIC monitoring for the qualitative and quantitative assessment of damage states, the full surface displacement field can also serve as input for the calibration and validation of numerical models, thus providing significant added indirect value.

The DIC monitoring analyzes on the shear capacity issue show that an efficient value generation associated with health monitoring requires also the incorporation of modeling information e.g. obtained from Non-linear finite element methods (NL-FEM). For instance a DIC verified NL-FEM can be used as tool for providing insight in the existing load level based on the monitored or identified crack pattern associated performance indicators. In addition it can be used to determine the load bearing capacity and hence for characterization of the consumable safety margin. Crack pattern associated performance indicators can be the following:

- Deformation parameters (displacements, distortions, curvatures of the model)
- Crack pattern development on the air-contacted surfaces
- Crack pattern development within the structural component
- Discrete and continuous strain fields on the air-contacted surfaces
- Discrete and continuous strain fields within the structural component
- Discrete and continuous strain fields of the reinforcement

To summarize, NLFEM models, adapted and verified by DIC observations, allows the characterization of the above mentioned performance indicators up to the load capacity of the considered structural component. The determination of the present stress level can be carried out on the basis of a selected group of PIs or a comprehensive consideration of the PIs and their correlation among each other. When defining the PIs, the measurement methods and their application possibilities to the real structure must be taken into account.

Closing paragraph: Joan, Konrad or Jose

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PROMOSS, COST TU 1406, COST TU 1402

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