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NON-LINEAR DIGITAL TWIN-BASED PERFORMANCE AND SERVICE LIFE ASSESSMENT

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Abstract: Many existing concrete structures have been fulfilling their purpose for several decades, but they may no longer meet current structural safety standards due to various factors. This fact highlights the urgent need for innovative solutions to ensure the durability and performance of these structures under increasing load and changing environment. Digital twins can indeed provide very effective solutions in various contexts. A digital twin is a virtual representation of a physical object or system that is used to simulate, predict, and optimize performance. By creating a digital twin, one can analyze data and monitor systems to prevent problems before they occur, develop new opportunities, and plan for the future by using simulations. In this work, we focus on the load-bearing behavior of a specially reinforced existing pier of the Jauntal Bridge in Carinthia (DT Physical Model). This behavior is virtually simulated using a non-linear finite element model (DT Virtual Model). The aim is to draw conclusions about the constantly changing load conditions by observing the development of cracks and the geometric deformations (DT Monitoring, e.g., via orthographic and radar interferometry) and thus to make statements about the constantly fluctuating safety level and the fluctuating service life. Based on these findings, it should be possible to optimize the existing verification formats and the arrangement of the reinforcement measures, particularly the prestressing bars and the interaction between new and old concrete at the pier heads. Consequently, this would allow for a direct assessment of the constantly fluctuating loads and safety levels.

1 INTRODUCTION

1.1 Digital Twin objectives and components

Digital twins have found their way into many areas of life, including understanding processes and analyzing and optimizing them in detail. In engineering, the digital twin (DT) method is becoming increasingly important and attractive, especially in the area of in-depth verifications, such as using non-linear numerical analysis methods. This contribution demonstrates how the digital twin concept was implemented to establish a continuous safety assessment and service life evaluation of a pier head reinforcement measure.

A digital twin is a virtual representation of a physical object, system or process that mirrors its properties and behavior in real or near real time. Digital twins are used to monitor, analyze and optimize performance by combining real-world data with models and simulations. A digital twin consists of three main components:

- Physical object: The real object, system, or process that is digitally mapped.
- Virtual model: A digital replica of the physical object that simulates its properties and behavior.
- Data connection: A continuous data connection between the physical object and the virtual model that transmits real-time data.

Nowadays there are already several standards and frameworks that support the development and implementation of digital twins. Some of the most important ones include:

- ISO 23247: This is an international standard specifically for digital twins in manufacturing. It provides guidelines for the creation and use of digital twins to improve manufacturing processes.
- ISO/IEC 30182: This standard provides a framework for the Internet of Things (IoT), which is closely related to digital twins. It helps in the integration and interoperability of IoT systems.
- Digital Twin Consortium: This is an organization that provides best practices, reference architectures, and frameworks for digital twin technology across various industries.
- Industrial Internet Consortium (IIC): The IIC offers frameworks and guidelines for the industrial internet, which includes digital twin technology. Their Industrial Internet Reference Architecture (IIRA) is particularly relevant.
- OPC Unified Architecture (OPC UA): This is a machine-to-machine communication protocol for industrial automation. It is widely used for the integration of digital twins with industrial systems.
- Building Information Modeling (BIM): BIM standards, such as ISO 19650, are used in the construction and building management industries to create digital twins of buildings and infrastructure.
- IEEE P2806: This is a standard for the framework of digital representation for physical objects in factory environments, which is essential for creating digital twins in manufacturing.

These standards and frameworks provide the necessary guidelines and protocols to ensure that digital twins are developed and implemented effectively, ensuring interoperability, scalability, and reliability.

Digital twins are used in many areas, including: (a) Manufacturing: Optimization of production processes and maintenance of machines; (b) Healthcare: Personalized medicine and simulation of treatment plans; (c) Urban planning: Development and management of smart cities; (d) Energy: Monitoring and optimization of energy production and distribution.

In this work, we focus on the load-bearing behavior of a specially reinforced existing pier of the Jauntal Bridge in Carinthia (DT Physical Model). This behavior is virtually simulated using a non-linear finite element model (DT Virtual Model). The aim is to draw conclusions about the constantly changing load conditions by observing the development of cracks and the geometric deformations (DT Monitoring, e.g., via orthographic and radar interferometry) and thus to make statements about the constantly fluctuating safety level and the fluctuating service life.

Based on these findings, it should be possible to optimize the existing verification formats and the arrangement of the reinforcement measures, particularly the prestressing bars and the interaction between new and old concrete at the pier heads. Consequently, this would allow for a direct assessment of the constantly fluctuating loads and safety levels.

Further advantages that generally result from Digital Twin (DT) analyses are:

- Improved efficiency: Bottlenecks can be identified and eliminated by simulating and analyzing processes.
- Cost reduction: Prediction of maintenance requirements and avoidance of downtimes.
- Promoting innovation: Enables new ideas and concepts to be tested in a virtual

environment before they are implemented in the real world.

Digital twins are a powerful tool that can revolutionize the way we understand and control physical systems.

The objective of this work is to demonstrate how the physical model of the pier head reinforcement of the Jauntal bridge can be transformed into a detailed virtual nonlinear numerical model. This includes also addressing the uncertainties that exist in the design, verification, and application of the reinforcement measures at the piers.

1.2 Digital twin of the Jauntal Bridge and its reinforced pier heads

The physical model for the non-linear numerical digital twin to be developed focuses on the reinforced pier heads of the Jauntal Bridge. The Jauntal Bridge in Carinthia, which spans 96 meters over the Drau Valley, is one of the highest railroad bridges in Europe. The single-track bridge, with a total length of around 430 meters, was originally built in 1961. Recently, the original steel box girder superstructure was replaced with a new structure that includes a double-track route and a footpath and cycle path underneath, shown in Figure 1.

During the construction process, the old steel structure was coupled with the new one, and both were moved together longitudinally to position the new structure correctly. The renewed bridge was opened to traffic at the end of 2023. Additionally, a comprehensive monitoring system was installed on the bridge to monitor both the construction and operational phases, enabling a thorough performance assessment.

The planning and construction of the new structure, shown in Figure 2, was carried out by the engineering office KOB and ÖBB Infra, with BOKU University as scientific partner assisting in the dynamic analyses and some detailed verifications of the bearings with shock transmitters. As can be seen in Figure 2(c) below in the bearing sketch, this is a special dynamically active bearing system in which the braking and earthquake forces are absorbed by hydraulic shock transmitters.

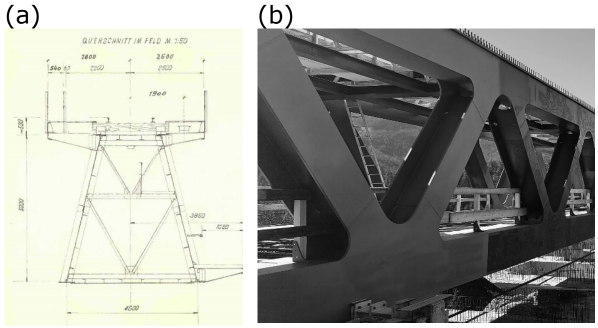


Figure 1 Jauntal Bridge in Carinthia (a) old steel structure cross section with a single-track line, (b) new structure under construction with a double-track line and a footpath and cycle path underneath

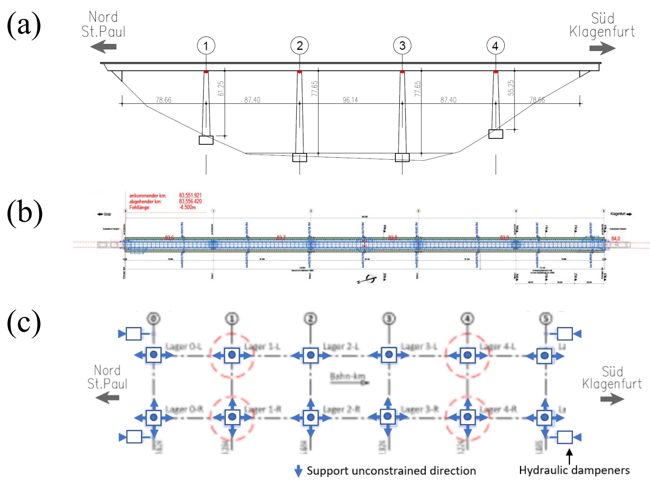


Figure 2 Jauntal Bridge in Carinthia, Austria (a) side view south, (b) top view on the double-track line of the new bridge, (c) bearing system of the bridge

The project included several innovative solutions to realize the double-track line on the existing piers and ensure its sustainable operation. A numerical, non-linear, in-depth digital twin was developed to verify that the 3D pier head strengthening system with prestressed bars, which included interaction between new and old concrete, met the load-bearing requirements for the increased structural and traffic loads. This non-linear digital twin verification also had to be approved and confirmed by an external expert.

2 VIRTUAL NUMERICAL MODEL

2.1 General basics

The loads of the new structure must be transferred to the old existing reinforced concrete piers via the supports and support bases, as shown in Figure 3a and Figure 3b. The bearing force at design level, which is the result of the self-weight, the removal loads, and the live loads of the structure, is a design load of 50 MN. The partial area pressure verifications for new concrete bearing soles on old concrete pier heads, shown in Figure 3, are usually interpreted very differently by the experts in accordance with EN 1992 [4] and sometimes lead to very unrealistic results.

The scientific partners created a real digital twin that corresponds to the possible verification procedures of Level III of MC2020 [5] and B4008 Part 2 [6] using non-linear finite element methods. As can be seen in Figure 3~~d~~, the pier head was additionally reinforced with appropriate tension rods to create an enclosure and increase the load-bearing capacity of the pier head. In addition, due to the significant uncertainties, probabilistic approaches were used to verify the existing capacity and safety.

2.3 Verification strategy

The verification strategy was developed in accordance with ÖNORM B 4008-2 Level III [6] and included the following main steps for modeling and verifying the concrete properties and structural behavior of the pier head and its interaction with the bearing concrete bases. The verification process comprised the following main steps:

- The extracted 36 cores from the pier heads were used, and the cylinder compression tests were re-modeled to obtain the statistical characteristics of the old concrete of the piers.
- The ??identity?? test results of the 76 cube tests according to EN206 of the concretes of the bearing bases placed on the old piers for the loading transfer were used and re-modeled in order to obtain the statistical characteristics of the new concretes.
- The numerical non-linear pier FE model was built in accordance with the planning documents, whereby no reinforcement was considered for the pier head in the first modeling level.
- In the second NLFE modelling level, the pier head reinforcement was only considered by loose prestressing bars without prestressing forces.
- In the third modelling level, it was assumed that 95% of the prestressing rods for the pier head reinforcement were applied simultaneously.

(a)

(b)

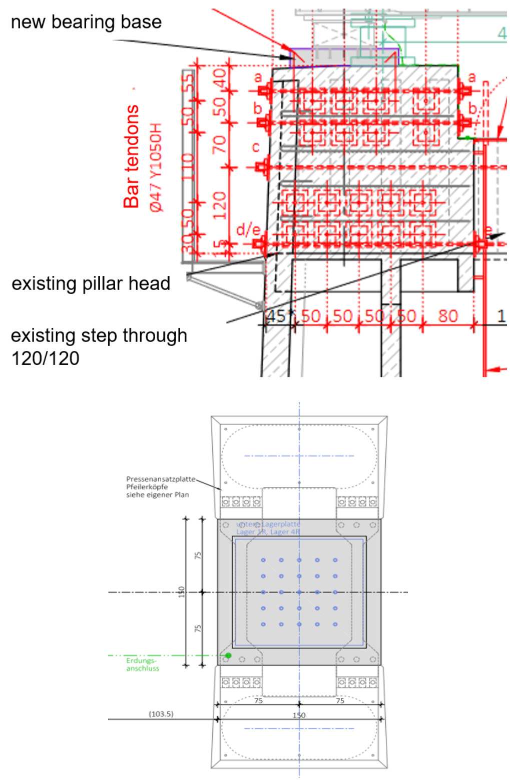


Figure 3 Bearing saddle and confined pier head, (a) in the longitudinal Direction of Bridge (Side View), and (b) on the top view of the saddle

Figure 4 shows excerpts of the results of the non-linear post-modelling of the identity cylinder tests of the old concrete of the pier head and its descriptive parameters, which were subsequently also used for the modelling of the digital twin of the pier head. The same procedure was followed to obtain the concrete characteristics of the bearing foundation from the identity tests of the cube compressive strengths, see Figure 5.

2.4 Characterization of concrete material

General basics: The concrete model CC3DNonLinearCementitious2 available in the ATENA software package [3] has been used to identify the previous mentioned test cubes and cylinders as well as the pier behavior. With the help of this material model, it is possible to take into account the material and geometric non-linearity and the material degradation due to cracking.

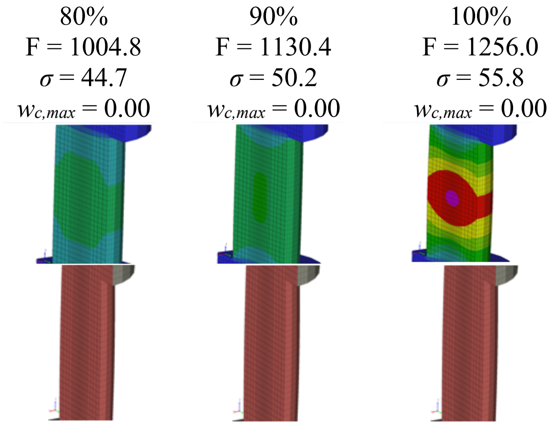


Figure 4 Results of the nonlinear post-modelled identity cylinder tests of the old concrete of the pier head and its descriptive parameters (F in kN, σ in N/mm², $w_{c,max}$ in mm)

Table 1 Descriptive material parameters of old concrete of pier heads, characterized using the CC3DNonLin-Cementitious2 model and the CEB-fib Model Code 90 [7].

Material parameter of old concrete	Value	Unit
Modulus of elasticity E	33253.6	MPa
Compressive strength f_c	37.0	MPa
Tensile strength f_{ct}	2.83	MPa
Poisson's-ratio μ	0.2	-
Fracture energy G_f	0.00014	MN/m
Plastic strain at strength f_c ε_{cp}	0.00133	-
Onset of crushing f_{c0}	5.95	MPa
Critical compressive displacement w_d	0.0005	m
Aggregate interlocking ON with Aggregate size	2	cm
Reduced f_c factor according to Collins & Vecchio	0.8	-
ρ -density	2300	kg/m³

The CC3DNonLinearCementitious2 material model implemented in the ATENA finite element program is based on the concept of smeared cracks and the crack band theory. The constitutive model is sketched by equation:

$$\boldsymbol{\sigma} = \boldsymbol{K} \cdot \boldsymbol{\varepsilon} \quad (1)$$

Here, **σ** denotes the stress tensor, **K** the stiffness matrix and **ε** the strain tensor. Figure 6 illustrates the key aspects of the used material model: (a) Non-linear behavior in compression. This refers to the material's response to compressive forces, which does not follow a simple linear relationship, (b) Failure in tension based on non-linear fracture mechanics. This describes how the material fails when subjected to tensile forces, taking into account the complexities of fracture mechanics, (c) Reduction in compressive strength after cracking: Once cracks develop, the material's ability to withstand compressive forces diminishes, (d) Stiffening effect in tension: This indicates that the material may exhibit increased stiffness when subjected to tensile forces, (e) Reduction in shear strength after cracking: Similar to compressive strength, the material's shear strength decreases after cracks form, (f) Two fracture models for crack development.

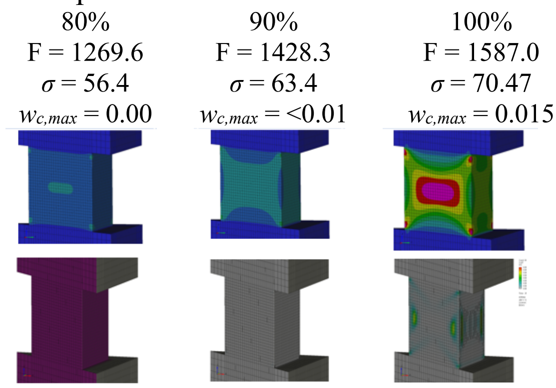


Figure 5 Results of the nonlinear post-modelled identity cube tests of the new bearing saddle concrete and its descriptive parameters (F in kN, σ in N/mm², $w_{c,max}$ in mm)

Table 2 Descriptive material parameters of new concrete of bearing sockets, characterized using the CC3DNonLin-Cementitious2 model and the C40/50 in accordance with ÖNORM EN 1992-1-1 [4]

Material parameter of old concrete	Value	Unit
Modulus of elasticity E	35000.0	MPa
Compressive strength f_c	48.0	MPa
Tensile strength f_{ct}	3.50	MPa
Poisson's-ratio μ	0.2	-
Fracture energy G_f	0.0000875	MN/m
Plastic strain at strength f_c ε_{cp}	0.000952	-
Onset of crushing f_{c0}	7.35	MPa
Critical compressive displacement w_d	0.0005	m
Aggregate interlocking ON with Aggregate size	2	cm
Reduced f_c factor according to Collins & Vecchio	0.8	-
ρ -density	2300	kg/m³

(2)

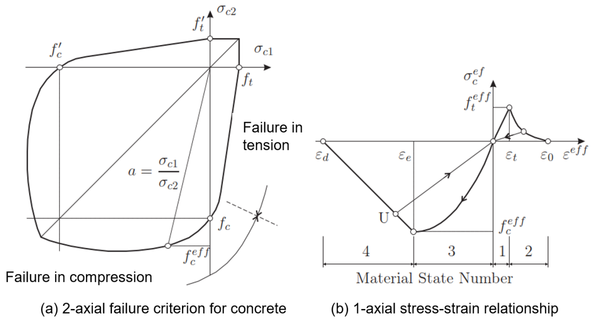


Figure 6 ATENA CC3DNonLinCementitious2 Material model [3]

These models describe the progression and behavior of cracks within the material. These points highlight the intricate and non-linear nature of the selected 3D material behavior under different types of stress and the importance of fracture mechanics in understanding and predicting failure. More details about the selected material models are given in the ATENA software theory handbook [3].

2.4 Pier head modeling

The numerically verified material parameters from the cylinder and cube simulations listed in Table 1 was used for the existing (old) concrete in the pier head models, as shown in Figure 7. These values represent mean values. A linear elastic material with a modulus of elasticity corresponding to that of C40/50 in the medium range was defined for the bearing socket concrete. The load was applied with a pre-scribed displacement. In order to determine the ssociated force a reaction monitor was defined in the linear elastic bearing socket plates.

The boundary conditions for modeling the constrained pier head were as follows:

- Plane of Symmetry and Restraints: The pier head is constrained in the plane of symmetry and restrained in the *YY* plane, as shown in Figure 7.
- Vertical Support: The pier head is supported vertically in the *ZZ* direction at a distance of 5 meters below the lower prestressing plane.
- Predefined Displacements: The predefined displacements were applied step by step centrically on the upper bearing plate in the *ZZ* direction.
- Prestressing Bars: Figure 7 shows the prestressing bars installed in different planes. It is assumed that equivalent anchorages are present in both ends.

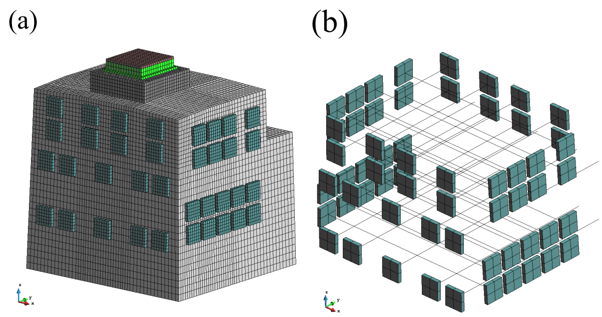


Figure 7 Virtual numerical model of a strengthened pier head, (a) Finite Element (FE) Mesh structure, and (b) Tension rod arrangement

3 DATA CONNECTION

3.1 General basics

The objective of the simulations was to analyze the load-bearing capacity of the pier head and its interaction with the bearing base made of new concrete, as well as to clarify the possible associated monitoring options. Additionally, the aim was to establish a connection between possible surface cracking and the externally observable deformation development during operation and before the ultimate load failure.

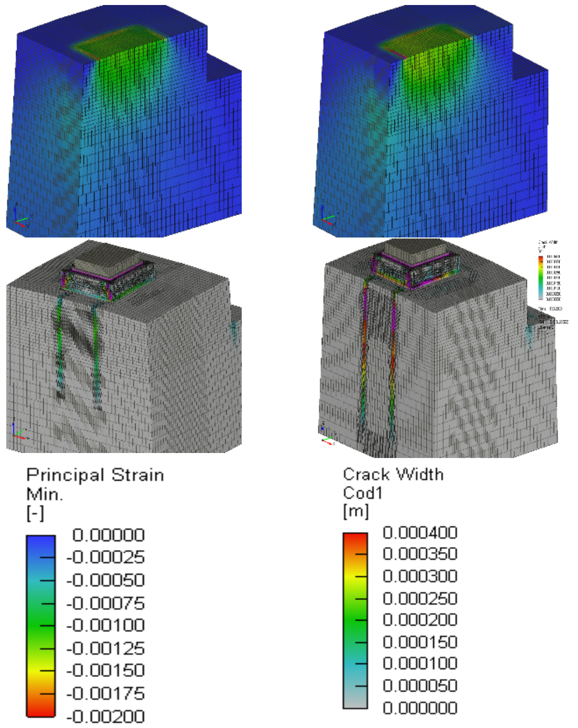
A photogrammetry and radar interferometry monitoring system are used to link surface and geometry information from the physical model's pillar to the non-linear finite element model properties (virtual model). This system is also operated during the operation of the Jauntal Bridge. For these studies, the client defined a maximum vertical force of 50 MN acting on the bearing block through the structure as a boundary condition, and a maximum permissible crack width of 0.1 mm in the old pier head concrete was specified as a limit value. These specifications were one of the main criteria for modelling, monitoring and assessment strategies.

3.2 Phases of the model analysis

The first phase consisted of analyzing the reinforced pier head ***without prestressing,*** shown in Table 3. The resulting maximum load-bearing capacity is 74.3 MN. Assuming a normal probability distribution and a coefficient of variation of 10%, the characteristic value, $N_{ck} = 62.3$ MN is calculated. Assuming a partial safety factor of $\gamma_c = 1.5$, the design value of the load-bearing capacity can be determined from the characteristic value with $N_{cd} = 41.7$ MN.

Table 3 Development of principal stresses and crack patterns with increasing load (Pier head without prestressing)

95% **100%**



In the second phase of the reinforced pier head analysis, the ***prestressing is activated*** in conjunction with the ***concrete deformation***, see Table 4. The prestressing was implemented in the model according to the specified plan]. For simplicity, no bond between the prestressing rods and the concrete structure was assumed.

The stress distribution plates were modeled as a linear elastic material with a modulus of elasticity of steel. The resulting maximum load-bearing capacity is 87.9 MN. Assuming a normal probability distribution and a coefficient of variation 10%, the characteristic value of $N_{ck} = 73.4$ MN can be calculated from the maximum load-bearing capacity, which represents the normative mean value. Assuming a partial safety factor of $\gamma_c = 1.5$, the design value of the load-bearing capacity can be determined from the characteristic value with $N_{cd} = 48.9$ MN.

In the third phase, the ***prestressing is activated*** through a direct application of the prestressing forces to the bars.

Table 4 Development of principal stresses and crack patterns with increasing load (prestressing activated in conjunction with the concrete deformation)

95% **100%**

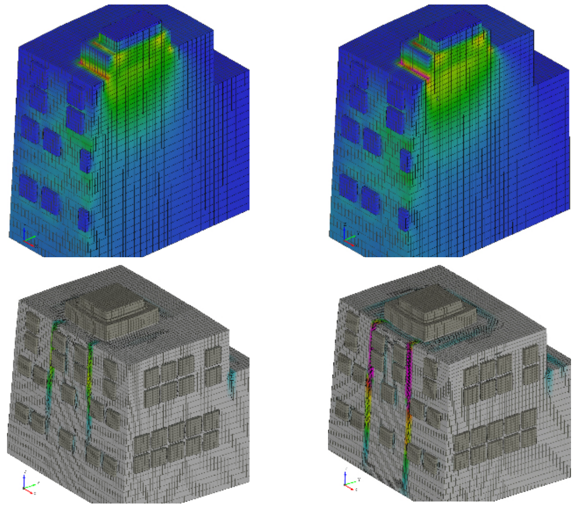
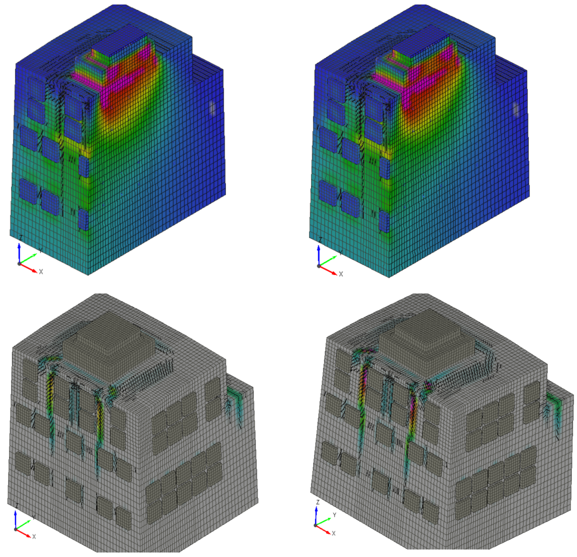


Table 5 Development of principal stresses and crack patterns with increasing load (prestressing activated in conjunction with the concrete deformation)

95% **100%**



In this phase, the following steps were implemented and results obtained: (a) a prestress force of $P = 1275$ kN was used., (b) The load was applied in approximately 250 load steps, (c) the maximum load capacity is obtained with approximately 141.1 MN, (d) the

characteristic value N_{ck} is calculated as 117.7 MN, assuming a normal probability distribution and a coefficient of variation 10%, (e) considering a partial safety factor $\gamma_c = 1.5$, the design value of the load capacity N_{cd} can be determined with 78.5 MN which complies the criteria of 50 MN.
The development of the load levels that can be applied, as well as the associated deformations and crack width developments, are summarized in Figure 8. It can be seen that the prestressing bars activated by deformation can already generate a load-bearing capacity of 50 MN and therefore the implemented solution fulfils the defined criteria.

The structural responses now available allow for a direct definition of the essential observation criteria for the operating photogrammetric and laser interferometric monitoring systems. This enables conclusions to be drawn from the observations regarding the load present on the bearings or piers.

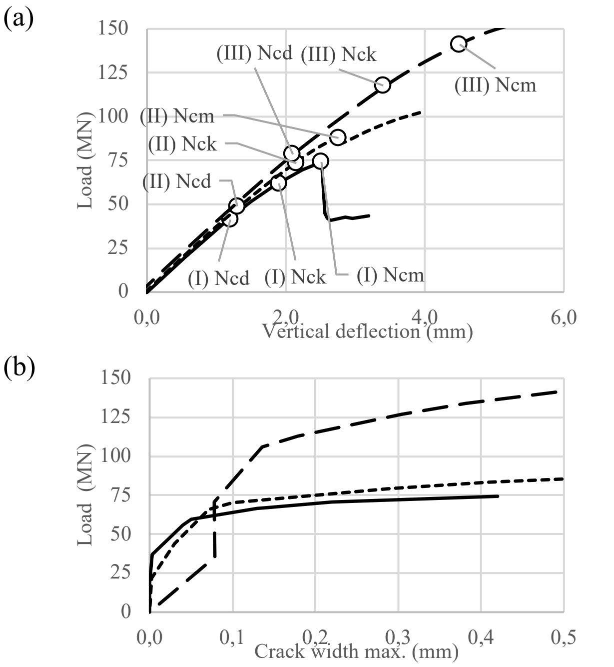


Figure 8 Load Structural response of first phase (I) ── second phase (II) ---- and third phase (III) — — diagram (a) load vs. vertical deformation, and (b) load vs. crack width development

4. ADDED VALUE OF DT ANALYSES

4.1 Iterative assessment and model update

The previous presented analyses are a base on some important assumptions, for instance such as the symmetrically and simultaneously applied prestressing systems and the symmetrical boundary conditions. A long-term observation of the deformations, as well as the crack pattern dynamics at the piers, especially in the prestressing area with the proposed monitoring systems, allows the adaptation of models using modern AI technologies and Bayesian updating procedures to determine a more accurate, reliability-based safety level.

Furthermore, in the next step, as soon as the first monitored deformations and crack patterns are available, it is of interest to reconstruct the non-symmetrical application of prestressing forces, which is common in practice, and to show the effect on the load-bearing capacity. This is one of the next projects in this research, particularly to demonstrate the efficiency of coupling photogrammetric and radar interferometric methods.

4.2 Prediction of the performance and service life

The DT modelling is crucial for predicting the service life of structural components such as the investigated strengthened pier, especially since it has theoretically survived already a service life of 60 years. Beyond the initial modelling process, we will extend the DT model to include the following aspects in the performance prediction over a defined useful life: (A) Durability: This refers to the ability of a structure to withstand wear, pressure, or damage over time. It ensures that the structure remains functional and safe throughout its intended service life, (B) Serviceability Limit State (SLS): This condition ensures that the structure remains functional and comfortable for users under normal conditions of use. It addresses issues such as deflections, vibrations, and cracks that could affect the usability of the structure, (C) Ultimate Limit State (ULS): This condition ensures that the structure can withstand maximum loads without collapsing. It deals with the strength and stability of the structure under extreme conditions, such as heavy loads, earthquakes, or strong winds.

CONCLUSIONS

The goal of this project was to demonstrate how a digital twin (DT) can be set up for a strengthened pillar head in order to evaluate the increased load capacity. In a subsequent phase, the DT will be adjusted using a photogrammetric and radar interferometer system. These digital twins subsequently allow for a more precise assessment of the current structural performance, as well as predictions about future performance and the remaining service life.

ACKNOWLEDGMENTS

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