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On systematic approaches for interpreted information transfer of inspection data from bridge models to structural analysis

master's thesis

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Abstract

In conjunction with the improved methods of monitoring damage and degradation processes, the interest in reliability assessment of reinforced concrete bridges is increasing in recent years. Automated image-based inspections of the structural surface provide valuable data to extract quantitative information about deteriorations, such as crack patterns. However, the knowledge gain results from processing this information in a structural context, i.e. relating the damage artifacts to building components. This way, transformation to structural analysis is enabled. This approach sets two further requirements: availability of structural bridge information and a standardized storage for interoperability with subsequent analysis tools. Since the involved large datasets are only efficiently processed in an automated manner, the implementation of the complete workflow from damage and building data to structural analysis is targeted in this work. First, domain concepts are derived from the back-end tasks: structural analysis, damage modeling, and life-cycle assessment. The common interoperability format, the Industry Foundation Class (IFC), and processes in these domains are further assessed. The need for user-controlled interpretation steps is identified and the developed prototype thus allows interaction at subsequent model stages. The latter has the advantage that interpretation steps can be individually separated into either a structural analysis or a damage information model or a combination of both. This approach to damage information processing from the perspective of structural analysis is then validated in different case studies.

Content

Abbreviations

AISTEC	Assessment of Aging Infrastructure Using Digital Technologies
BDM	Bridge Design Model
BIM	Building Information Modelling
BMS	Bridge Management System
BREP	Boundary Shape Representation
BS	Building Smart
CAD	Computer Aided Design
CSG	Constructive Solid Geometry
CV	Coordination View
DIM	Damage Information Model
DTV	Design Transfer View
FE	Finite Element (Modeling)
FEA	Finite Element Analysis
FIB	The International Federation for Structural Concrete
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
LCM	Life-Cycle Management
MVD	Model View Definition
SA	Structural Analysis View
SAM	Structural Analysis Model
SHM	Structural Health Monitoring

1 Introduction

The latest report on the climate emergency declared by more than 11000 scientists [1] is devastating. An unfavorable socioeconomic pathway can threaten the fate of humanity [2] and I have little to contribute to a brighter future in this thesis. The reason is that "digitalization" (hype) has not proven its value to society in this context yet. So far, processes that widely take place in the digital world like social networking, information retrieval and trade have simplified and increased consumption e.g. Facebook, Netflix, Amazon [3]. *Information and communication technologies are further criticized due to the high resource use of their infrastructure* [4]. *This work is about digitalization in the sense that it expects increasing efficiency if processes in structural engineering make use of these new technologies. But as long as products and concept are developed out of a mere sales potential and the value for society and the environmental impact are not judged a sustainable socioeconomic pathway remains questionable. Hopefully, the ideas introduced in the following can be used to extend the service life of a structure and not to determine an economically preferable rebuild.*

1.1 Target

The construction industry is affected by the ongoing digital transition i.e. building information modeling (BIM) being the domain-specific developed concept. So far, the main advances have been the major development of tools facilitating planning and design activities, data management and the exchange between stakeholders. However, most of the related processes are not implemented completely but progress in digital methods, collaboration and standards has been made.

Assessment of aging infrastructure using digital technologies (AISTEC) is an interdisciplinary project at the Bauhaus-Universität Weimar at the Chair of Modeling and Simulation of Structures and the Chair of Computer Vision in Engineering. Herein, a software-assisted image-based structural health assessment of bridges is carried out targeting "efficient, transparent and well-documented infrastructure inspections in a life cycle context" as stated by Morgenthal et al. [5, p. 93]. Up-to-date, anomalies and deficiencies, e.g. cracks, can be automatically detected from images taken by an unmanned aircraft system and referenced to the surface of the bridge structure by the viewpoint. In this image-based process, the surface model is derived from a point cloud reconstructed with photogrammetry. This model alone presents not enough information to transfer the gained knowledge to subsequent analysis tasks and further data sources need to be considered. A promising approach is to use an intermediate step, i.e. link structural information also related to further sources in a central data model [6]. In other worlds, a building information model for life-cycle engineering tasks needs to be maintained. Using a classification scheme here, damages could be prepared for an automated evaluation procedure. In conclusion, a systematic transfer to structural analysis is then possible. The latter is of high value in the domain since damages are usually small and often do not severely influence the load-bearing behavior but accumulate in total. Assessing damage in structural analysis models is thus often omitted due to its unfeasible realization using manual modelling techniques. But if the individual extent and evolution of every damage is modeled automatically, predicting the critical state and the reliability of the bridge becomes possible.

Not only damages but also building elements need interpretation in a transfer process. Automating the transfer of building elements from BIM authoring tools to discipline-specific design and analysis software is thus a recent challenge targeted by multiple software vendors since the major benefit of avoiding redundant design activities is easily understood. This process involves not only the import and export of building information but also its interpretation, best visualized with an example. From an architectural point of view, the joint between a column and a slab is sufficiently modelled if both geometrical entities implicitly touch each other. However, the structural analysis model is only consistent if the topological relationship of these entities and the type of connection is defined. The latter requires the interpretation by a structural engineer, i.e. human interaction. Especially, in bridge engineering complex structural analysis models are needed to accurately represent all mechanical aspects, additionally in this work to consider structural damages. Thus, a flexible and customizable procedure, i.e. a derivation strategy, that allows semantic changes of the transferred building information while minimizing postprocessing tasks is targeted. Moreover, different finite element modelling approaches, i.e. ways to model the mechanical behavior of a building model, are possible. The resulting mechanical systems vary in their representation of the stress state and hence consider the effect of damage artifacts in different ways. In an automated process, it is impossible to guarantee unlimited freedom in modelling. However, it is important to compare the different techniques to identify their impact on the automated derivation process and the resulting prerequisites that might limit the structural designers in their work.

The objective of this work is to address the lack of interoperability between building information models and structural analysis software in bridge life-cycle engineering. The result of this work is the implementation of an exemplary workflow interpreting and transferring building elements and damage information in separated steps to structural analysis. Requirements on the data structure and transfer from the point of structural analysis as well as damage modeling are elicited. As a basis, state-of-art interoperability formats, finite element (FE) modeling technique of bridges, damage analysis using nonlinear FE simulations, possible damage classification and information modeling are described. Automation is introduced with commercial and scientific approaches deriving structural analysis models in different ways and building representations. The following guiding questions are then used to assess these approaches and to identify the requirements on the implementation.

- Which BIM data structures exist that facilitate the modelling and processing of structural damage and analysis models?
- Which requirements on damage information models are imposed by the finite element design of structural damages?
- Which existing transformation methods can be reused or adapted to transfer and interpret building information especially structural damages of reinforced concrete bridges?

A case study using simple bridge elements is carried out and the performance of the implementation assessed. In this work, the focus is on widely spread reinforced concrete girder bridges. Other types like cable stayed bridges are out of the scope of this project.

1.2 Methodology

The methodology used in this work adapts some concepts from model-driven software engineering [7]. In particular, the development process distinguishes between the *problem space* and the *solution space*; While in the groundwork (section 2 to 5) the involved areas of knowledge are analyzed, a subsequent collection of requirements and design considerations enables the implementation (section 6). To address the problem space, a *domain analysis* is carried out "to study the knowledge-domains as thought or discourse communities, which are parts of society's division of labor" as expressed by Hjørland and Albrechtsen [8, p. 400]. In this sense, concepts of the three identified domains – structural (reliability) analysis, damage modeling and these processes in an automated context – are evaluated to decide which aspects need to be part of the scope. In other words, the target is to find out distinct features which are then arranged in a suitable domain model [9]. At this point, problems of the domains shall be clear and requirements can be collected and described in order to identify implementation artifacts more easily. The domain concepts are viewed here from the developer's perspective [9]. In general, no new ideas on how to carry out research are introduced but the different mindsets and point of views in this work are explicitly stated.

2 Interoperability and Standardization in BIM

Projecting a building is a unique process similar to developing a new product. Different stakeholders from various fields come together and begin every time the design, construction, calculations, analysis from scratch. Standards present guidance on how and when to carry out a specific task and how the final products needs to perform but no outline is presented on how to collaborate. *Building information modeling* (BIM) originally is proposed to solve this issue with standardized definitions, workflows and exchange formats but vividly spread out as a synonym for the digital transition. BUILDINGSMART (BS) [10] influenced the development from the beginning targeting uniform standards around the world. Out of their slow progressing, software companies like AUTODESK [11], BENTLEY SYSTEMS [12] or NEMETSCHEK [13] presented their own BIM-centered solutions and custom workflows. Currently often used in practice, they present an alternative to the open standard support by most governments. As a result, the latter lacks usage. This solution of BS is the vendor neutral building information exchange format IFC (Industry Foundation Classes). Using it, geometry and semantics can be exchanged but only for coordination, a so called “round-trip” which is crucial in the domain enabling edits and changes is not fully supported up-to-date. Approaches towards a design transfer view are made in the current proposal. However, the procedures of extending the format are still rigid and slow provoking criticism. Nevertheless, its usage is enforced by governments at the moment which makes it important to consider and its value for this work is illustrated in the following. First, the characteristics of bridge design and its representation in IFC are described. Subsequently, the implementation of the structural analysis domain is assessed resulting in a discussion of its potentials and limits.

2.1 Design and Modeling

The superstructure of bridges as the main load bearing element is characterized by one dimension being significantly bigger than the others. Hence, in many cases when modeling the superstructure, it can be idealized as a profile swept along a predefined alignment curve i.e. the main axis (see Figure 1). The latter is usually extracted from the infrastructure project and minor changes are allowed during the structural design phase. On the other hand, defining the cross-section is part of a form finding process that aims for an optimal distributed load bearing capacity of the bridge body since self-weight accounts for a large proportion of the total loads. As a result, freely defined cross-sections and varying profile parameters, e.g. the girder’s height, along the main axis are often applied.

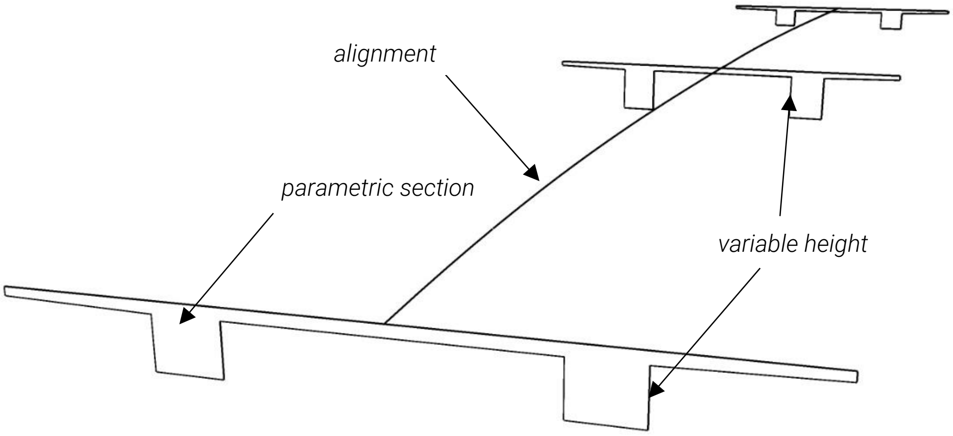

Figure 1: schematic illustration of the superstructure of a double T-beam bridge

As such, bridges differ from standard building elements and domain-specific highly specialized software is employed for their design. Parametric modeling is embedded in many of the related systems allowing fast design changes and optimizing the structural design. The bridge's geometry is then generated from a set of parameters, geometrical constraints and interdependencies between them, often from underlaying sketches as well. Naturally, flexible models are created facilitating the form finding process. Moreover, the parametric description presents a simple and consistent way to transfer the geometry [14], calibrate the model by records of the as-built or deformed state [15] or reuse them in multiple projects. Despite its many advantages, parametric geometry is not incorporated in the new IFC 4X2 draft [16], [17] (planned for IFC-Bridge 2.0) and geometric bridge models can vary from extruded to boundary shape representations (BREP).

Dealing with existing bridges, structural information might be only available in low-level digital formats like PDFs; a format that is only human-readable and thus requires a rebuild of the structure for subsequent calculations. New methods of collecting geometric information like laser scanning or image-based reconstruction are proofing themselves as valuable tools but an inherent problem is their ability to capture only the explicit geometry. In particular, the point cloud scan can be transformed to a surface model but important attributes like material parameters, cross-section dimensions, reinforcement layouts, slab thicknesses or even hidden structural elements like diaphragms are still missing. In conclusion, it requires tedious manual reentering of data to build a consistent model to be used for maintenance tasks like structural health assessment. Automatic object recognition from point clouds transferring the content to implicit geometry definitions using structural meaningful entities can support this process but remains an unresolved problem [18]. However, both science and authorities identified this problem and for future projects new guidelines demand the delivery of as-built building information models after completion which simplify data management and maintenance to a major existent [19]. Those digital representations are a key element for the application of automated documentation and information extraction methods and it has to be ensured that different design philosophies and isolated systems of automation do not impede these processes. Hence, identifying the main requirements on the building information model from the herein presented workflows will facilitate the usage of digital methods in future.

2.2 Ongoing Activities

The Industry Foundation Classes have a vivid history of development which is comprehensively documented on the BS web page [10] or in [20]. Compared to pure geometric descriptions like WAVEFRONT OBJ, a domain-specific and standardized data format for the exchange of digital building models including the semantics of its components is provided for architecture, engineering and construction. Extendibility is foreseen with a layered structure specifying domain, interoperability, core and resource entities [20]. As such, new entities and their definition are integrated in a hierarchical structure. Apart from the standardized extension mechanisms provided by proxy entities and property sets, new official versions by BS are steadily proposed including new concepts. In the current IFC4X2 version [16] the results of the IFC-Bridge project [17] are incorporated. Such extensions are specifying the exchange requirements of domain-specific information transfer. In this sense, bridge design as a part of infrastructure projects is separated into use cases describing requirements on the representation of geometry or sematic information in the model e.g. for quantity take-off the explicit geometry is sufficient while a design-to-design transfer will need to persist a full parametric description. The current state covers only a selection of the derived use cases due to the limited time, resources of the project and its scope to lower the effort of implementation [17]. After such a feasibility study, a process map is developed incorporating the targeted used cases with is roles and workflows. As a result, the information quality of a transfer i.e. its functional parts are specified and *model view definitions* (MVD) are proposed which define the technical implementation using a subset of model entities from the IFC schema [20]. It is then expected that software companies will adapt the specifications by the MVD. The presented methodology is based on *information delivery manuals* (IDM) established in the standard ISO 29481 [21]; the reader is referred to [20] and [22] for a detailed description. In general, a concept similar to requirements engineering in software development is carried out depicted in Figure 2. In the IFC-Bridge project, use cases are linked to specific geometry representation which facilitates the derivation of the following basic MVD.

- ***Bridge Reference View (RV):*** includes explicit geometry definition using BREP and cartesian coordinate for positioning.
- ***Alignment-Based Bridge Reference View (ARV):*** is an extension of the later incorporating the alignment and referenced positioning.
- ***Bridge Design Transfer View (DTV):*** targets a design transfer for referencing (not full model logic) supporting advanced geometry definitions.

As already stated in the previous section, usually the complex shape of bridge superstructures requires an implicit definition e.g. sweeps consisting of the two-dimensional cross-section and its variation along the bridge axis in order to allow a transfer of the design intent. The latter is supported in the current proposal of the design transfer view with the IfcAlignment and IfcSectionedSolid entity but only in a referenced way and exchanging or editing parameters is not enabled. Hence, the full model logic cannot be restored by the receiving application. On the other hand, the first step towards bridge information models is made and the IFC schema is completed with missing building elements; see [17] for an extensive description of the introduced concepts and IFC components and modifications. Additionally, an approach towards modeling of defects as surface features is made but no MVD or analysis of the scheme concerning life-cycle engineering is given (the reader is referred here to section 4.2 for further discussion).

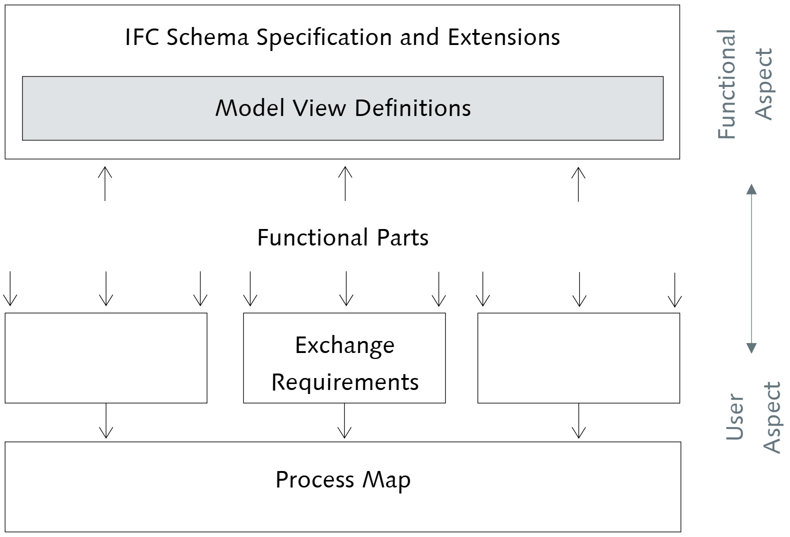

Figure 2: Development process of the information delivery manual and model view definitions adapted from [22]. A separation into the implementation (functional aspect) and the description of workflows and exchange requirements (user aspect) is depicted. Hence, meaningful documents for users and programmers are derived.

A much earlier BS Project “Structural Analysis and Steel Construction” (ST-4) [23] is concentrated on the integration of topological representations for building elements into the IFC schema to enable its usage in the structural engineering domain. At this stage, the concept of MVD is introduced and the *Structural Analysis View* (SA) is one of its first applications still being the latest version. Focusing on the raw design in the planning phase, the major identified use case is the derivation process of a load-bearing system from the architectural building representation. Thereby, structural idealization to a reduced 3D or even 2D subsystem including only the load-bearing members is an important step. Hence, new entities are introduced, in particular, structural points, curves, members and surfaces enabling the design of common structures like trusses and frameworks. In contrast to architectural entities, they are defined in the same coordinate system so that members can share structural points; a relationship entity defines the mechanical connectivity at this level. Additionally, external impacts can be integrated using load entities and their summarization in load cases. In total, a representation of the load-bearing system of steel constructions from the perspective of structural analysis is targeted. In this context, the IFC extension provides decoupled structural elements to enable their transfer, but no recommendations for the derivation from commonly shared building elements even though the link is obvious. From the perspective of structural analysis this concept is very meaningful because the structural idealization process is part of the responsibilities of structural engineers as further assessed in section 3.1. Depending on the structure and material, completely different concepts can be applied. Out of this variety in interpretation possibilities, projects for reinforced concrete (ST-2) and precast concrete structures (ST-3) are initialized at the same time but the outcome and incorporation in the IFC schema is unknown to the author [24]. As such, exchange requirements of the latter are not recognized and potential limitations exist, but expendability and flexibility of the ST-4 proposal is ensured according to Weise et. Al [23]. Software vendors in the domain like DLUBAL [25] or SOFISTIK [26] implement an interface to IFC in this manner enabling the transfer from their side. However, up-to-date BIM centered solutions are still not supporting the MVD leading to an incomplete hand over and an unknown workflow to the interest group.

2.3 Potentials and Limits

From the last section, it becomes apparent that the concept of MVD is only meaningful if implemented by software companies. But only the most general definition, the *IFC2X3 Coordination View* (CV 2.0), is widely used for different purposes currently; even as an alternative in the structural analysis domain (see the DLUBAL [25] interfaces or path B in Figure 3). Unfortunately, the wide spectrum of geometry representations and building entities allowed by this MVD unnecessarily complicates the transfer process and leads to unsatisfying results since domain specific information like explicit connectivity statements is lost at the same time. The original intent of testable exchange requirements incorporated in the transfer format is not accomplished here. The latter presents a crucial element to reduce the complexity of the IFC schema to a sufficient set of entities increasing its usability and management. Hence, it is expected that the rising necessity of specialized transfer processes will facilitate the use of the MVD concept [20]. Ramaji and Memari [27] propose a conversion of the MVD concept due to its current misuse. They view the model presented in the IFC 2x3 CV 2.0 or DTV in IFC 4 as a centralized exchange platform that corresponds to a BIM model making all needed information openly available to the stakeholders. Then, interpretation tools derive the domain specific MVDs from the Master-MVD and the outcome of their task is returned to the latter in a direct transfer. As such, the presented approach is in accordance with asynchronous collaborative data administration leading to a structured information resource. This way, the manner of organizing and coordinating a project is fixed which might be interesting in some scenarios but in other not, especially, if only a single transfer is requested. Moreover, the implementation effort for a participating software company is decreased but the total effort is increased since three transfer steps are involved; from a design tool to the master model to the domain-specific representation and then to the others software's data model depicted in path C in Figure 3. In total, MVD can help to simplify and ensure consistency in a domain-specific information transfer in advance. A conforming interpretation of the building model is usually subject to the sending tool as comparing all available information to the required one is only enabled here (see path A in Figure 3). A subsequent application or an outsourced tool to translate MVDs can only process the presented information, i.e. make implicit facts of the model explicit as further described in section 5.2.2. For this work the idea of MVD to isolate a use case, i.e. the purpose of the transfer process from the complete domain needs to be discussed as well. Its advantages become apparent if two of the applying model purposes are compared. For the design and structural definition of a bridge it is important that structural information like cross-sections and relative positioning to the alignment are explicitly formulated while the geometry can be implicitly defined based on these entities. On the other hand, a digital twin of the bridge shall represent the physical reality as precise as possible including deviations from the design thus explicit geometry statements are used which contain structural entities like the cross-section at a specific station (curve parameter) only implicitly. Hence, these two use cases are difficult to unite and MVD anticipates this problem. However, they restrict their reusability at the same time, e.g. damages should be part of the digital twin but in order to analyze them structural information and considerations of the design need to be available. At first sight, this seems impractical here but this way a workflow-oriented solution is enforced. Concerning interoperability, the key idea is not to make all information available but only the required parts in a predefined format which is advantageous for subsequent processing steps. In particular, the latter leads to two separated workflows. A *Structural Analysis Model (SAM)* is derived from the design model of the bridge (Design Transfer View). A *Damage Information Model (DIM)* is related to the digital twin (Bridge Reference View) but needs to establish a link to the design model as well. This way, the SAM can be adjusted to include the damages and structural information using both models. Concluding, the workflows targeted in this work use a broad spectrum of entities from the building, damage and structural analysis domain which are analyzed from the perspective of life-cycle management in order to identify the functional parts and exchange requirements.

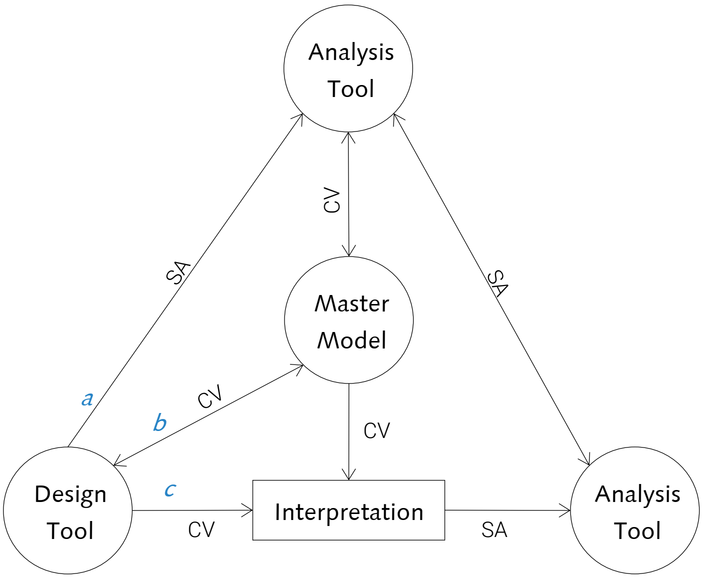

Figure 3: Different possibilities of transfer processes are shown. In (a) a direct transfer is shown which requires both tools to implement the corresponding MVD. In (b) another exchange is realized via commonly shared building elements. No direct import is possible for the analysis tool; interpretation is needed and potentially not all available information is exchanged. In (c) an alternative to (b) is displayed that outsources the interpretation process to an external tool.

3 Finite Element Design of RC Bridges

Finite Element Analysis (FEA) is widely implemented in structural analysis software and presents an enormous value to structural and mechanical engineering. It allows the accurate simulation of whole structures under different load scenarios as well as modeling and studying deformations, stress and strain states of structural details. In other words, it assists engineers in their work to analyze the load bearing behavior. Complex numerical models, especially material models, for reinforced concrete design taking into account stiffness reduction from crack formations and the yielding of concrete in confined setups have been developed based on observations from experiments and are nowadays used for practical design without the possibility to verify these results with experimental data. On the other hand, the complex nonlinear behavior of reinforced concrete is often simplified with elastic material models in order to understand the load bearing behavior without the use of computer calculation at all and hence are widely used for teaching purposes and design. Of course, numerical models are a simplification of reality as well and consider only chosen effects. A proper check of the results obtained by numerical simulations is needed but becomes difficult with only a simple material model in mind or a non-transparent modeling approach. In conclusion, it is important that structural designers can understand and control all inputs of their simulations in order to be able to verify the outputs.

In this chapter, the reader is briefed with considerations and important steps in the finite element design of reinforced concrete bridges and the attention shall be drawn on the challenges to incorporate them in an automated process. Hence, only a coarse overview of FEA is given, detailed descriptions can be found in [28]–[30], also used as a guide for the following sections. Especially, the modeling of structural damages and special features of as-is models are reviewed since it is of major interest in this work to obtain potential requirements from these models.

3.1 Structural Idealization

The given double T-beam bridge from Figure 1 is taken exemplary to demonstrate model preparation in FEA and the interpretation step in the transfer process called *structural idealization*. First, for the sake of understandability only the superstructure is considered. This is in conformity with the standard approach of splitting the structure into partial models. Critically reflected, this separation is difficult to incorporate in an automated process. Design changes and model updates can only be considered if the geometry of all components is coupled which needs a complex background management routine. Further, this approach facilitates smaller and clearer models, however results in the need to define multiple boundary conditions in order to model the stiffness distribution and force transfer correctly. Extra work is required, especially in integral bridge design, since determining the stiffness of separated parts involves a load test, i.e. an additional simulation. For the beginning, note that it might be desirable to split the structure into smaller, more processible models.

Secondly, the aim is to represent the structure with reasonable simplicity and accuracy that is conductive to FEA, i.e. ensure that the mechanical behavior is accurately calculated and the simulation can be evaluated. In this work, only the idealization of the structural system is assessed, however load models play a major role in this process as well. For instance, modeling the superstructure can be carried out with beams elements that are computationally cheap and easy-to-interpret or with shell and volume elements that allow a detailed representation, further assessed in section 3.2. Choosing the beam elements their finite element formulation has to be considered. Most implementations only consider non-warping, laterally stiff *Bernoulli* beams with a linear strain distribution. While this is an accurate assumption for box and plate girders, the double T-beam section suffer from significant section deformation when a non-symmetric load is applied, e.g. on only one web. A single beam model would result in a critical underestimation of the overall deformations. Hence, a multi beam approach, illustrated in Figure 4, refines the chosen approach where the influence of the section deformation is considered with separated elements in the transverse direction. Additionally, for a complete design using the beam approach another model for the complete cross-section design is needed.

As mentioned before, modeling the stiffness distribution correctly is a key element in the idealization process due to its direct relationship to the load bearing behavior. Apart from geotechnical constraints on the foundation, boundary and transition elements like joints or bearings can influence the overall structural behavior to a major extent. Usually, they are mechanically separated parts specially designed for a controlled transfer of forces and deformation behavior. These regions are characterized by concentrated forces and significant nonlinear strain distributions further assessed in section 3.3 as *discontinuities*. Hence, the *Bernoulli Theory* cannot be applied and those regions also need further refinement. Damages like cracks can also cause a severe discontinuity in the force transfer and a decrease in stiffness, i.e. plastic hinges, that might be incorporated differently in the model, further assessed in section 3.4.

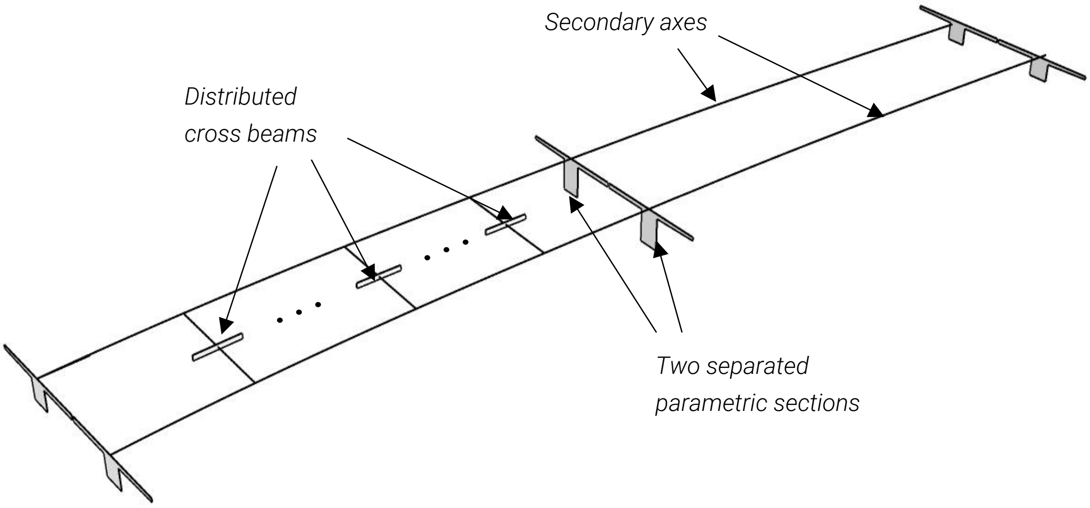

Figure 4: schematic illustration of the grillage model approach for structural analysis of a double T-beam bridge. The secondary axes are derived by a shift of the alignment to the web centerlines. An effective width is calculated for the two separated parametric cross sections. Alternatively, to the pictured cross beams a shell element can be used.

Reinforced concrete in the cracked state is considered with another material model because its behavior in this stage is highly nonlinear as previously stated [29]. Since reinforced concrete is a composite material governed by bond and the distribution of reinforcement in the concrete matrix, two very different constitutive laws and a uniting mechanical model are necessary. To understand this concept and its impact on the results is part of the analysis, however, the idealization of the material is subjected to research and standards. Since nonlinearity introduces a considerable amount of complexity and requires expert knowledge, its usage is only justified if the improved accuracy is important for the overall analysis. Reasons can be the consideration of load redistributions, the exact determination of deformations and the analysis of cases of structural failure and damages, all being part of the analysis of the ultimate limit state. In particular, for statically indeterminate systems where failure is not reached when the load bearing capacity of the load-bearing member is exceeded and redistribution of forces can occur, nonlinear material analysis is crucial [28]. It has to be ensured that brittle failure i.e. the ultimate failure condition of concrete is prevented. To be sure about a well performing structural analysis model parameter studies and the consideration of boundary values might be necessary.

Concluding, structural idealization is a highly individual task. Guidance can be given by standards, however, being a main part of the responsibility of structural engineers this process has to be controlled by them. A structural analysis model is not only a data model it is also a flexible tool for the structural design and assessment of the load bearing behavior and can be generated correctly in different ways.

3.2 Element Formulations

One of the first choices in a structural idealization process is the selection of the element type or formulation. Elements are derived from the mathematical formulation of a mechanical problem i.e. the terms beam, plate or slab are mechanically distinguished by the decisive load direction and the geometrical dimensions [29]. Hence, the governing strain state of any member of the bridge body is predicted and elements are chosen accordingly depicted in Figure 5. Various finite element formulations of mechanical theories exist and their implementation in the used software has to be assessed for the range of application. Due to this variety, only the fundamentals of different modeling approaches are given in this section.

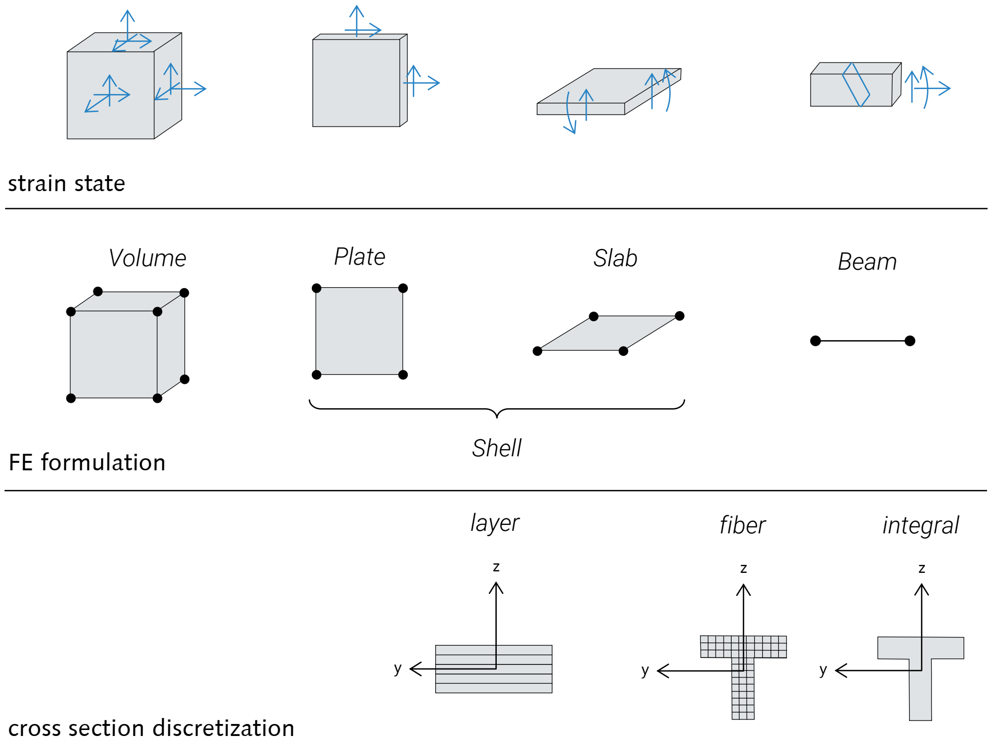

Figure 5: overview of applied finite element formulations and their distinct mechanical features. In the first row, the governing strain state is illustrated. The finite element formulation is named in the second row and different cross section discretization are presented, especially important for nonlinear material modeling of reinforced concrete

Aiming for reasonable simplicity and accuracy, usually beam elements are chosen in bridge engineering since they are computational inexpensive and allow a direct calculation of internal forces. As stated before, the mechanical assumptions of the beam theory have to be met in this case, in particular a linear strain distribution. The structural analysis model is then developed accordingly using the central axes of the superstructure or piers and the specific cross-section so that the FE model can be derived by automatic meshing algorithms. The same strategy can be applied to slab, plate or shell elements using a reference plane and a corresponding thickness. Most design software models these elements in a similar way facilitating the derivation process. Volume or solid elements are usually avoided in structural engineering since their use contradicts the idea of structural idealization and processability, further, interpreting results becomes more difficult. On the other hand, the development of *isogeometric analysis* [31] allows to create a direct link from NURBS-based geometric CAD models to FEA. Yet, most BIM authoring tools have not implemented NURBS-based geometry and this approach is not applied in the building sector, an exception is presented in [32] using mechanical design software for bridge engineering. Concerning the analysis of reinforced concrete structures (with a nonlinear material model), the reinforcement and tendon layout needs to be modeled in a discrete way using bar elements or smeared on a concrete element. The discretization of the cross section contains then for example fibers or layers having assigned material laws for reinforcement, concrete in the uncracked or cracked state (see Figure 5). When carrying out a linear-elastic analysis, it is advantageous to compute only the stiffness contributions of the rebars. On the other hand, tendons as the key element of prestressed concrete structures require more attention equally in design and reliability analysis. They are modelled either in a discrete way applying a normal force on special beam elements or curvature loads are computed from the prestressing force.

Even though, bridges usually have a great longitude span which is also the main load bearing direction, attention has to be paid to the transverse direction as well. Since dimensions e.g. of a box girder section are significantly bigger than usual beam cross-sections, distortion is expected for unfavorable load positions and an additional analysis is carried out. Often a model consisting of beam elements for the longitude direction and a transverse model consisting of beam or shell elements are developed separately. Moreover, regions subjected to a redirection of forces, e.g. the support positions on piers need constructive strengthening measures like diaphragm and are assessed separately as well. This approach is conductive to the initial design. However, assessing the as-is state with the occurrence of structural damage might require a more wholistic approach further described in section 3.5. For example, a model approach using shell elements could predict the major deformation behavior and stresses in both directions correctly [28].

3.3 Discontinuities and Transitions

For the whole design and assessment of the structure, the identification of discontinuity regions is necessary (see Figure 6). These regions mainly develop from two sources: disturbance from concentrated loads and disturbance from changes in geometry. Examples are supports, tendon anchorage, openings, frame corners, discrete cracks, bends or abrupt changes in the cross section. They are characterized by a significantly nonlinear strain distribution, the main reason why most beam theories[1] are not applicable. Neglecting their influence would result in an underestimation of displacements, poor life-cycle behavior and even failure since a clear check of stresses is not included [33]. The linear strain distribution corresponding to the Bernoulli Theory will develop at some distance away from the disturbance, as the *Principle of Saint-Venant* states. Following that idea, the dimension of the discontinuity region can be found (see [33] for further description). In other words, discontinuity regions cover the part of a structure where the uniform stress field is disturbed. Proposed by Schlaich [33], *strut-and-tie models* are utilized as a basic tool to detail these complex structural elements, calculate ultimate limit loads and have an insight in the internal force flow. Up-to-date, they are generated by hand and computational methods - if at all - are used as a check. FEA of these regions is indeed relatively complex since it is necessary to represent concrete in a multi-dimensional strain state, discretize the reinforcement layout and nonlinear material models are required to determine the stress state and ultimate failure accurately. Such a modeling approach needs a discretization with planar or solid elements, a high number of degrees of freedom and hence considerable computational effort. However, the use of a more processible model consisting of Bernoulli beams is only justified if attention is drawn to the discontinuity regions. Here, the inadequate assumptions in the numerical model will produce stresses and internal forces tending towards an infinite value called *singularities*. The obtained results cannot be considered for design and the average or a value some distance away from the discontinuity is taken. In any case, the identification of singularities and their source facilitates the understanding of the structural behavior since they evince discontinuity regions or regions actually subjected to high stresses where cracks presumably form like sharp corners. As previously stated, a consistent design involves however a more detailed model. The question arises if it is easier to generate a partial model and a corresponding spring with a nonlinear force displacement relationship in the parent model or to incorporate the modeling approach in the global model. Combining

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[1] Apart from Bernoulli and Timoshenko beam theories more complex approaches considering shear deformations exist. These *High Order Beam Theories* are based on nonlinear strain distributions for example a quadratic approximation.

beam and planar elements is possible. However, singularities are introduced when they are coupled directly node-to-node and an analysis of this region is thus impeded. Moreover, not all connection types can be modeled due to the incompatibility of the stiffness matrices concerning the beam's rotational degrees of freedom. Such transitions in the modeling technique needs careful assessment and an approach that satisfies displacement compatibility and stress equilibrium. *Mixed-dimensional coupling* equates the work done on both sides of the interface e.g. coupling a 1D beam to a 2D plane allowing an accurate force transfer [34]. Attention has to be paid on locating the coupling a feasible distance away from the perturbation of stresses and strains to justify the linear strain distribution in Bernoulli beams. However, modeling a stiff transition, often an alternative method of extending the beam element into the plane is chosen. The transition is moved away from the area of interest and the incorrect results obtained in the transition area are neglected. Concluding, the identification and modeling of discontinuity regions in structural design is important, especially, to control cracking. Different philosophies considering the treatment of singularities or their avoidance exist. Simulating the structural behavior of a discontinuity regions introduces considerable complexity and modeling effort but allows a clear determination of stiffness crucial for the overall analysis.

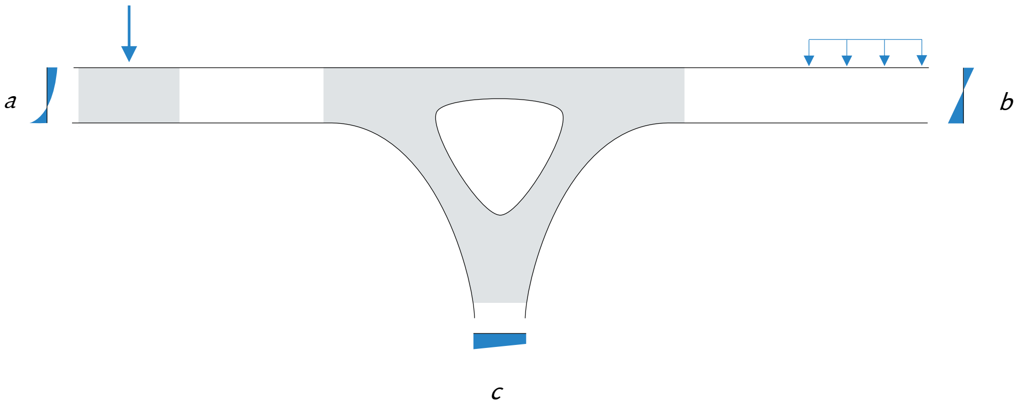

Figure 6: In detail a) a load induced discontinuity is shown. Compared to detail b) the strain distribution is significantly nonlinear. Thus, the Bernoulli Theory cannot be applied since the constraint of an even strain plane within the cross section is violated. Discontinuities can also result from changes in the geometry as shown in detail c). At some distance away from the disturbance their effects can be neglected.

3.4 Material and Damage Models

3.4.1 Continuum Damage Mechanics

Nonlinear response of reinforced concrete structures is usually expected meaning that the relationship between applied forces and displacements cannot be described with a linear function. Instead, the deformation behavior is divided into an elastic and plastic range (see Figure 9). The latter can be identified via the residual displacements after a load cycle, i.e. permanent strains indicating a change in material properties. Reinforced concrete under tensile force will undergo a drastic change with the occurrence of cracks, so that material models often view the cracked state as a new material [35]. In other worlds, a load-induced mechanical damage process has happened [36]. However, micro-cracks in concrete itself do not represent a severe defect. Deterioration, i.e. damage accumulation, plus the exposure to chemical and physical impacts leads to further reductions of strength, stiffness and dimensions [37]. To assess the difference of load-induced and load-independent damage processes in FE simulations, important material properties of reinforced concrete for *continuum damage mechanics* and an overview of damage modeling are given in the next sections. In the following, it is assumed that mechanical damage happening on the macroscale can be combined with continuous strain fields and hence the phenomena can be incorporated into a material model to a sufficient level of accuracy for engineering purposes, see [29], [38] for further information. Fracture mechanics and the discrete modeling of cracks are not assessed in this work.

3.4.2 Material Properties of Reinforced Concrete

As long as no cracks occur in the concrete continuum, standard procedures following the linear-elastic theory can be applied. In contrast, cracked reinforced concrete structures are characterized by a different strain distribution, stress redistribution resulting in a complex stress state. Stress redistribution will mainly result in a concentration of tension forces in the reinforcement while compression stresses will concentrate in the non-cracked parts [33]. This response can be observed when increasing displacements and crack patterns on a real structure.

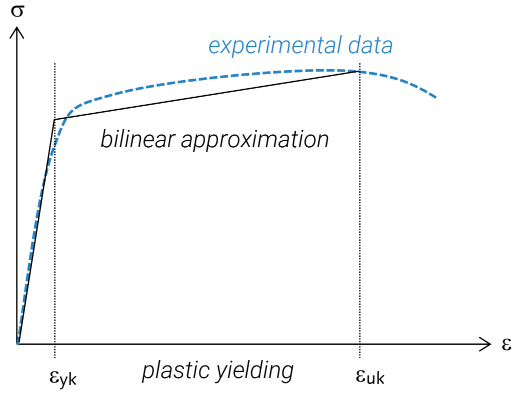

Figure 7: The elastoplastic behavior of reinforcement steel is characterized through an initial elastic part, a large yielding part with increasing strains and a short softening part. It has the capacity to severely deform without reaching a critical state (roughly $\varepsilon_{uk} = 50*\varepsilon_{yk}$). Stiffness does not change during loading and unloading resulting in a higher yield stress after each load cycle also called hardening.

Since the behavior of concrete depends on the distribution of reinforcement, meaning that the internal structural system is a priori defined by the designer, concrete stresses need to adapt themselves to the assumed internal structural systems restricted by its characteristics. Normally, concrete allows only limited plastic deformation meaning that the rotation capacity of the whole structure is limited. The chosen internal structural system needs to fulfill the criterion that the deformation limit is not exceeded at any point before the assumed stress state is reached in the rest of the structure. This is the main criterion when assessing the ultimate limit state. Predicting the respond of reinforced concrete structures in any state depends further on the following criteria [29], [35], [38]:

- ***Load-induced anisotropy:*** Reinforced concrete does not reach failure with cracking. A lower stiffness and strength of pre-cracked concrete can be observed but compression and shear forces are still transmitted due to closing of cracks or aggregate interlock.
- ***Multiaxial stress state:*** Behavior and strength are different in fields with pure compression, mixed tension-compression and pure tension. Generally speaking, the strength of the concrete in compression fields depends to a large extent on its multiaxial state of stress and on disturbances from cracks and reinforcement.
- ***Discontinuous strains:*** Stresses in reinforcing bars vary. At crack locations highest stresses and yielding are observed while between cracks tensile stresses exist also in concrete, resulting in nonlinear strains and complex stress states. Formulating relations based on average stresses is convenient.
- ***Ductility:*** In order to reach the stress limit states a large redistribution of internal forces may be necessary. This requires large deformation and thus ductility of the whole structure.

The latter applies mostly to mixed tension-compression fields. Areas where forces are exchanged are required to have large enough strains with a nearly constant level of stresses. This is fulfilled by the reinforcement (see Figure 7) but not necessarily for concrete. Concrete in a confined or cracked state shows in some cases ductility but this needs to be evaluated carefully. Neglecting the Poisson effect, a uniaxial compression state in a planar set up can be assumed, but only if the compression strength of an unconfined set up is used (see curve b in Figure 8). The strength of concrete in compression fields is a function of the lateral strain i.e. latter cracks reduce the concrete compressive strength named strain softening. Hence, it might be necessary to reduce the compression strength to an effective strength when moderate lateral strains occur, and transverse reinforcement is needed. Considering the Poisson effect on the opposite, also allows higher compression strength and ductility of reinforced concrete in compression regions and not only in tension (see curve a in Figure 8). In total, one could speak of a stress-induced orthotropic material behavior [29].

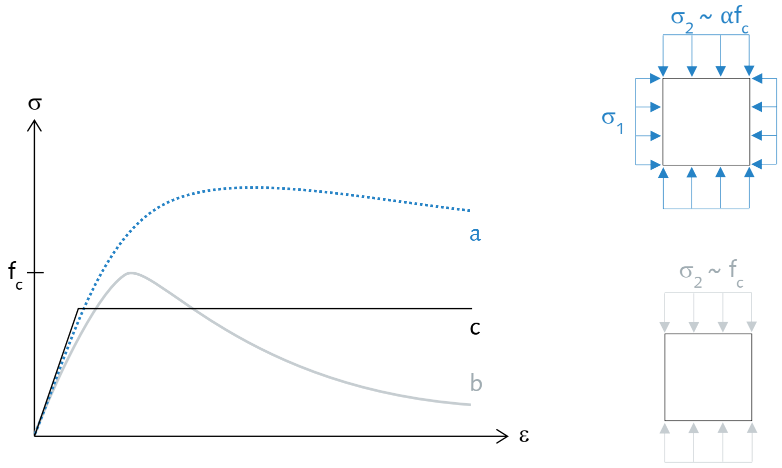

Figure 8: stress-strain relation of concrete showing that under lateral compression or a confined set-up (curve a) ductility can be observed while unconfined concrete (curve b) behaves significantly different. Curve c represents an elastic-perfectly plastic approximation of concrete. Note that in the case of concrete the simplification of reality is much greater compared to steel.

Any constitutive model must link the stress-strain relation and strength in such way that the consistency of the material description is assured [29]. Within the stress-strain relation, decreasing tangential material stiffness i.e. load-induced anisotropy mainly strain softening and tension stiffening can be described. It is advantageous to use the *principal stress or strain state* to include the dependency on the lateral strains in the material model. Cracking i.e. the largest principal stress reaches the uniaxial tensile strength and the direction of cracks can be easily determined in a simplified manner. This approach is called *smeared crack modeling* since the phenomena is not assessed in a direct way but averaged over a certain crack-band, see [29] for a comprehensive review and [35] for a popular implementation. If a uniaxial strain state is dominating in a structural member, i.e. beam elements, the smeared crack model can be applied as well. However, structural damage incorporated into the material model does not allow a clear determination of crack location, only some area of cracking due to its calculation in the integration points of the used elements. In conclusion, not all effects of cracking are addressed but load-induced anisotropy is modelled in a reliable way. Hence, results in good agreement with experiments are obtained [29].

3.4.3 Damage Modeling

Continuum damage mechanics present a valuable tool to assess all kinds of mechanical damage [38]. It has been shown in the previous section that the load-depending deterioration of structural stiffness and resistance can be modeled, but no direct implementation of damage was described. Due to the time-variant nonlinear nature of the deterioration process damage accumulation needs to be described in a time dependent way. However, occurring instantaneously or over a life-time and from various origins this is an ambitious task [36]. Assessing the as-is state on the other hand needs several assumptions regarding the deterioration state. Affected structural properties can be the dimensions, stiffness or strength of a member. While the latter two are best mapped to the material matrix, reduced dimensions influence the geometry i.e. cross-sectional parameters. The different strategies could be executed in the following way.

- If the dimensions are affected, e.g. chloride penetration with corroding reinforcement, the effective tensile area needs to be reduced. Carrying out a parameter study using a deterioration variable in this case allows the identification of critical points in the load-bearing behavior, e.g. the formation of plastic hinges. For a more sophisticated analysis the deterioration variable can be time dependent and related to concepts from degradation models [37].
- If stiffness and strength of concrete are influenced from load-independent processes, e.g. freeze-taw cycles, a similar procedure can be applied. Here, material properties of a certain region are used as input variables.
- If a loss of mass, e.g. spalling, was identified at the as-is state a non-effective area can be applied to the region. A parameter study in this case is linked to the geometric entity and the severity of the defect can be assessed directly.
- If stiffness and strength of concrete are influenced from load-cycles a careful evaluation of the load model is needed. Simulating mechanical damage with FEA allows to identify critical points in the load-bearing behavior. However, relating the outcome to the as-is state is difficult without proper validation data like experimental load-displacement diagrams or measured modal parameters [39]. On the other hand, crack patterns from inspections can be used for a visual comparison that can allow conclusions on the decisive load combination [36].
- Tendons represent a special case since they are usually regarded in a load case. In this sense, the latter has to be adapted if prestressing or the effective area is decreased. Their importance for structural safety and the structure's possibly high sensitivity to changes in prestressing make them a key element in damage modeling [40].

In reality, degradation processes are much more complex. A mechanical damage will lead to a weak point for carbonation, depassivation and ultimately rebar corrosion even with a loss of bond or spalling (see section 4.2.1). A whole field of research in material science is dedicated to describe these processes in *degradation models*, an overview is given in [37], an example how to use them for safety analysis and reliability assessment is given in [40]. These models are definitely needed for the development of reliability models. Using continuum damage mechanics, a direct link between nonlinear material behavior and degradation models is permitted. A probabilistic concept can be introduced with them, on the other hand, FEA is usually used for failure analysis in a deterministic way [40]. Hence, different ways of assessing structural failure together with model validation possibilities are given in the next section.

3.5 Reliability Analysis and Model Validation

In structural analysis damage is best measured in the time evolution of the tangential stiffness matrix. The stiffness contribution of all structural damaged and undamaged members is summarized in here. Its most condensed form is represented by the eigenvalues that can be used to easily compare the as-is state with the original state and to derive *damage indicators* [36]. Carrying out a parameter study using a deterioration variable as described before or increasing the loads, such indicators allow a sensible tracking of the damage evolution leading to structural failure. Petryna and Krätzig [36] demonstrated their significance with various examples but they also name the many uncertainties in relating damage indication to life-time estimates.

In this field, structural health monitoring represents the most reliable tool to quantify structural damage of the as-is state. Structural parameters like deformations or crack width or modal parameters like eigenfrequencies, mode shapes and damping ratios can be identified in a non-destructive way with sensor technology. Two monitoring systems are possible. Either deteriorations are localized in advance and its structural parameters like strains in this region are measured, called *bottom-up approach*, or the structural behavior is measured with a sensor network independent of damage localization, called *top-down approach* [37]. Both determine parameters that can be used as direct inputs into FE *model updating* [37], [39]. This procedure optimizes the correlation between experimental and analytical structural parameters, i.e. an existing FE model can be updated to fit the monitored behavior. An important step is the selection and tuning of updating parameters that are closely related to damage modeling. If a region of damage and the affected structural properties (dimensions, stiffness or strength) are known and parametrized, the extent of the degradation is tuned until correlation of the measured parameters is met. An important prerequisite for the functionality of the method is the preparation of the FE model for such analysis, in particular, boundary conditions plus the mechanical system also in details need to be accurately modelled and matched with experimental values from the undamaged state. Features that are usually neglected for structural design are required in here leading to much more complex models [39], [41]. Processability of such detailed models can be reached with the *substructuring method* [30] i.e. static condensation and mass lumping reducing the degrees of freedom to a major extent, an example is given in [41]. In conclusion, the analytical model can be validated and structural failure can be determined in a more reliable way allowing life-time estimates with fewer uncertainties. However, a quantitative statement is rarely made at system level [37]. Apart from the deterministic view on structural reliability also *probabilistic models* to consider statistical uncertainties in material properties, load or damage models and process can be introduced. Here, distributions are used as a time-to-failure measurement i.e. a time dependent description of the health condition is enabled [40], [42]. This concept introduces changes to damage modelling in the sense that a probabilistic approach to model degradation as further described in section 4.2.1 is chosen. However, the strategies to describe damage are assumed to remain the same and for the prototypic character of this work such an analysis is not needed to be considered.

Concerning reinforced concrete structures, the assessment of the ultimate limit state and failure is especially important. As already explained in section 3.4.2, they have a limited rotational capacity meaning that plastic deformation with a redistribution of forces may not be in conformity with a fail-safe design since brittle failure cannot be excluded in some cases. Hence, assessing damage with a deeper insight into the mechanical behavior allows a clear statement if planned plastic deformation capacities still exist in the current state of the bridge. This means that failure analysis is either carried out on the most sensitive member or if not clearly identifiable on the whole structure. On the other hand, the serviceability limit state has to be evaluated and guaranteed as well. Further, the results of this analysis can lead to maintenance recommendations.

4 Damage Identification in Life-Cycle Management

What fascinates most civil engineers about building is the planning and building process itself and little attention is paid to the major life-cycle phase which is maintenance. In recent years the ailing infrastructure in Europe became known and the development of maintenance concepts is becoming a key element in the planning process reducing the overall costs by considering the maintenance effort of building components. Also, digitalization is extending its concepts towards the operational phase and tries to illustrate its value with the acronym "BIM-BAM-BOOM" highlighting the Building Assembly Modeling (BAM) and the Building Owner Operator Model (BOOM). In Bridge Engineering, maintenance consists mainly of identifying deteriorating parts and their treatment since structural sustainability and stability is easily affected (see Figure 9).

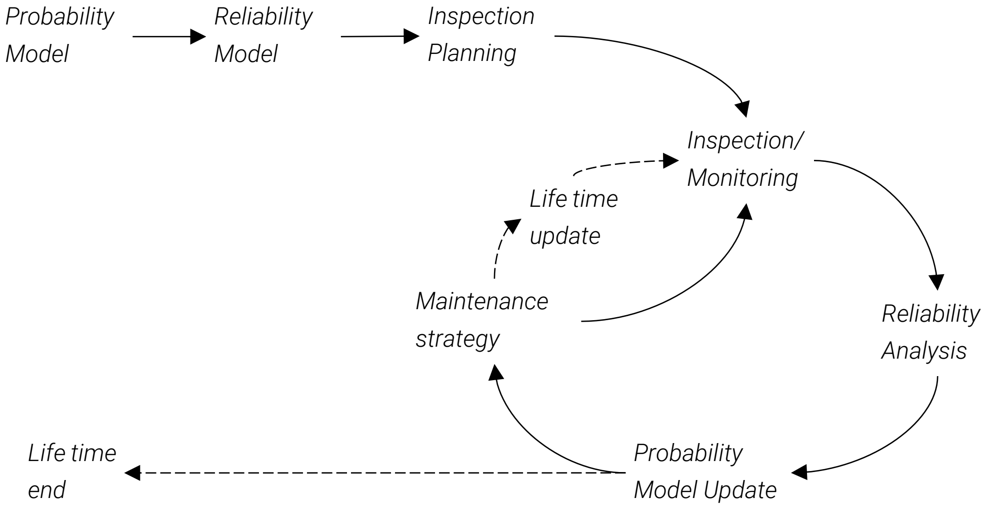

Figure 9: Elements in an integral life-cycle management; the probability model determines the potentials and risks while the reliability model prognoses the deterioration and failure of members. The inspection or monitoring identifies damages and allows a more precise reliability analysis and hence an update of the probability model supporting the decision-making process whether to invest in maintenance work or not.

However, the diagnosis of the structural health condition is not so straight forward. Conventional maintenance manuals like DIN 1076 in Germany [43] require extensive visual inspections of all structural components close at hand of experienced bridge inspectors. Their task is to assess the state of use based on the survey. A drawback of this method is that visual appearance and structural reliability often differ and engineers assess and classify the damage based on intuition, past experience and so-called good practice. Consequently, surveying data is used as a reference not for information extraction and a strong interest in reliability-based methods exists [37]. Sensor-based structural health monitoring (SHM) is already widely used and offer direct input values into structural condition and reliability models usually assessing the mechanical system with finite element models. The information gain from such models allows a more objective investigation of the damage and fracture mechanisms. Enhancing objectivism in bridge inspection is targeted in the AISTEC project as well. The basis for an information-based decision-making process is formed by the automated identification and localization of defects from images. However, its potentials arise in combination with further assessment methods e.g. identifying problem zones for a bottom-up monitoring approach. More recent guidelines like the FIB model code [44, p. 368] therefore name "feasibility of evaluating the condition ‚… predictability of the service life ‚… recording and quantification of the actions that occur during the service life of the structure" as important elements of conservation strategies. In this section, the reader is introduced to damage identification in life-cycle management, the classification of damages in a machine-readable format, i.e. damage information models and the management of building and bridge inspection data being the base for further assessment methods.

4.1 Inspection and Monitoring

The wholistic approach to study the complete life-cycle of a bridge with its planned usage, costs, environmental impact and its role in the overall context of the infrastructure project has more and more impact on the engineering design in recent years. The past experience shows that future traffic loads were difficult to predict, maintenance costs are increasing unproportionally even requiring a premature rebuild in some cases. This situation has led to low-maintenance designs, e.g. integral bridges lacking mechanical bearings. However, such a design also includes a maintenance concept and some cases a build-in monitoring system [44]. SHM methods have proven themselves as a valuable source for reliability predictions, assessed by Strauss et al. [37], also used as a reference for the following sections. On the other hand, in many countries well-developed infrastructure exists where a retrofit with monitoring systems in many cases is simply uneconomic and visual inspections are still viewed as the basis for life-cycle management (LCM). Unlike monitoring systems, visual inspection does not present direct input values into reliability models and the classification and validation of damages including the determination of causes and consequences for future usage is done by specially trained bridge inspectors guided by directives like the RI-EBW-PRÜF in Germany [45]. Accordingly, attributes of the classification are structural integrity, road safety and durability. Software solutions called bridge management systems (BMS) like SIB-BAUWERKE [46] support this process by means of damage examples, a framework to add further information and a standard conform bridge condition rating. The given score together with annotations on element level shall provide guidance for decision making, the extent of the maintenance work and the reliability of the bridge. However, important elements of LCM (see Figure 9) like the prognosis of degradation or the life-cycle assessment are not included in this method rising the need for an integral LCM approach. Of course, the damage identification still remains the basis but the current BMS implementations limit the usage for further processing mainly out of the following reasons taken from [5], [47]–[49].

- Inspectors register defects and damages in an analogue manner, e.g. sketches, photos, notes, voice memos which are then used as a comment or annotation for the given assessment score leading to a non-transparent derivation process.
- Damages are linked to nominal bridge components and no building or defect geometry is given. This abstract data is not only difficult to understand without having a proper visualization. Also it does not allow further processing, e.g. images of defects cannot be properly referenced without the camera position and orientation. Further, photogrammetric reconstruction requires a high resolution of images.
- Damage is stored in an isolated form and no semantical relation to other components or previous damage is given. Hence, understanding the extent of a defect or comparing the extent with a prior report entry is difficult (Tracking the deterioration over time is an important element in LCM).
- The systems are diverse and non-interoperable so that the data basis of inspection reports cannot be shared. This is a classic problem of information islands, i.e. the unnecessary need to re-enter data for further processing, e.g. for structural analysis.
- Damage characteristics as well as their testing methods, e.g. how to measure a specific property, and interpretation are loosely regulated leading to subjectivity in the classification process.

On the contrary, modern BIM authoring software will need extension to support damage information and classification as well rising the need for new approaches and data models. The inspection intervals regulated by DIN 1076 present a huge potential for the accumulation and interpretation of data. The outcome is not only interesting for authorities and maintenance; such long-term data sets could help scientists to study deterioration mechanisms, structural behavior, load cases and various other topics. Therefore, “collaboration of all stakeholders i.e. authorities, builders, engineers and scientists is needed” as formulated by Strauss et al. [37, p. 74].

4.2 Damage Information Models

4.2.1 Damage and Degradation Processes

An inspection can identify damage as the effect of a *degradation process*. Further, inspectors can identify weak spots where a degradation process has started depicted in Figure 10. The latter does not necessarily imply already occurred damage. For instance, carbonatization is a perpetual process dependent on environmental influences like the humidity, material properties and the diffusion at the concrete's surface [37]. Load-induced damages, i.e. cracks increase the available surface plus the penetration depth and therefore boost the degradation process. The progress and severity have to be tracked in this case and might lead to recommendations for maintenance. Hence, it is necessary to regard not only the effects but also its causes and derive a consistent classification in this sense.

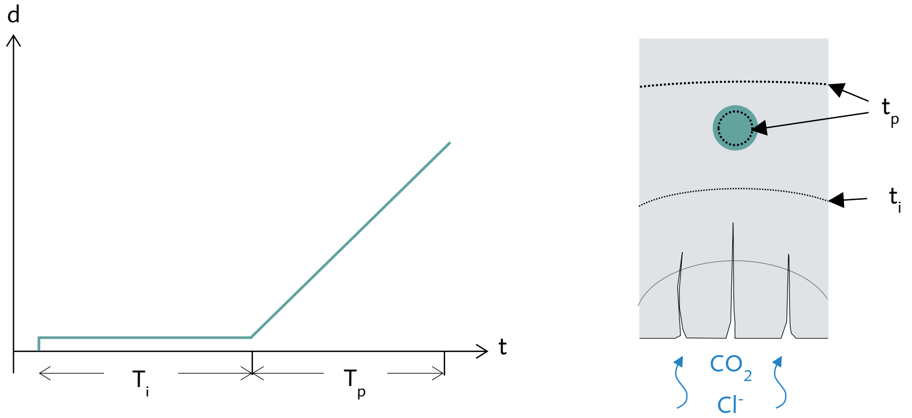

Figure 10: displays the most common degradation process of RC structures characterized by rebar corrosion adapted from [20]. A weak point, e.g. a mechanically induced crack, determines the start point of concrete depassivation meaning that the pH-level is reduced. Its progressing (T_i) is strongly correlated to environmental impacts e.g. carbonatization or chloride penetration (initiation phase). In (T_p) the critical pH-value of 8.3 around the rebar is already reached and corrosion i.e. damage (d) occurs (propagation phase).

A primarily distinction should encompass load-induced (mechanical) and load-independent (chemical, electrochemical or physical) damage. Describing degradation processes opens a vast field of research; models vary widely in their complexity e.g. linear or probabilistic and the number of input parameters, an overview is given [37], [38], [50] used as a reference here. To understand their significance for damage information models, the most common deterioration mechanism of reinforced concrete structures is depicted in Figure 10. Hereof, two concepts can be derived. First, load-induced, mechanical damage can be the source or an amplification factor for load-independent degradation. Second, deteriorations affect reinforcement and concrete differently which implies a differentiation between the *initiation and propagation phase* for the assessment of serviceability. Since carbonatization itself has no significant effect on concrete's stiffness or strength but could cause severe corrosion and thus damage of the reinforcement, a registration is needed together with its progress. As already stated, it is difficult – if not impossible – to determine structural health solely from the visual appearance. As such, an estimation of the degradation progress can only be made on a very coarse level by inspections, e.g. specifying the current phase. However, this information is crucial for further assessment; a bottom-up monitoring approach benefits from this data plus it supports model calibration. In addition, frequently not only a single degradation process occurs, rather, a combination of multiple impacts and their interaction has to be regarded. In this sense, the chronological order can present valuable information for the understanding of damage propagation (see again Figure 10 for illustration). Another distinction can be made by the location and extent, in particular, to allow reference to the affected building element(s). The extent can be described on different levels ranging from the complete element to a specified region or detail. In this way a first estimation regarding the severity and consequences can be made. For instance, if a progressing chloride penetration is found, it is essential to determine if structural integrity of the deteriorating part can still be assured. A known reinforcement layout in this region for assessing the load bearing behavior is a prerequisite in this case. Targeting an automated workflow, degradation processes and affected structural parameters shall be mapped to support the set-up of structural analysis as described in section 3.4.3. A simple classification is depicted in Table 1. Proposed is then a parameter-based reduction of the effective load bearing area, the stiffness or strength of a specific region according to the mapping. From this perspective, a discrete representation of the damage, e.g. a crack, is not needed. The damage extent is rather expressed element specific, in particular, as a section of a beam or a polygonal space of a slab. This approach facilitates modeling of damage propagation as well allowing a link to the degradation process. For example, the boarder of a damage area could shift with every registered progression.

Cause	**Concrete**			**Reinforcement**		
	dimension	stiffness	Strength	dimension	stiffness	strength
carbonatization				**x**		
chloride penetration				**x**		
sulfate attack	**x**	**x**	**x**			
abrasion/ erosion	**x**			**x**		
freeze-thaw-cycles		**x**	**x**			

Table 1 relates a selection of mechanistic empirical degradation models for reinforced concrete structures with the affected material and property taken from [19]. Here, a simple mapping between affected structural parameters i.e. dimensions, stiffness, strength and degradation process is given.

Up to now, only load-independent processes are regarded. A first attempt to regard mechanical damage processes could be to supplement Table 1 since stiffness and strength are affected. But in this way, the cause is not really mentioned nor related. Mechanical damage is load-induced meaning that a certain load-case e.g. temperature, shrinkage/creep, traffic loads or a combination of the latter can be identified as the cause. As already stated in section 3.4.3, the structural analysis modeling approach is completely different then. Since serviceability design shall prevent large deformations and crack width, the resulting damage is usually small and has a neglectable impact on the structural performance. A diverging inspection registration after completion indicates either a deficiency in design or construction. On the other hand, noticing significant mechanical damage in a later life-cycle stage implies increased loads and the assumed load model needs to be corrected. In any case, a review of the building's reliability using structural analysis is needed as addressed in section 3.5. Concluding, damage accumulation and degradation processes are inherently different. However, from the perspective of inspections they both needed to be registered. A damage information model shall therefore supply comprehensive semantics that model and assess effects and cause. As stated in the FIB model code [44, p. 379] "structural performance must be determined from the results of the inspections/surveys and/or monitoring carried out and by using appropriate models for the mechanism(s) of deterioration".

4.2.2 Implementation Attempts

Damage information models address the insufficient performance of damage modeling in BMS by introducing BIM concepts. The aim is to compose a system that characterizes, structures, categorizes and relates structural damage and building elements semantically as well as geometrically. Up to date, no standardized scheme exists and the development is carried out by research. An overview on implementation attempts is given by Artus and Koch [47] who compare and try to evince individual potentials and deficiencies. In general, the classification of damage is identified as the main task in all of the related works. As a start, possible classifications are derived from the considerations presented in the previous section and depicted in Figure 11.

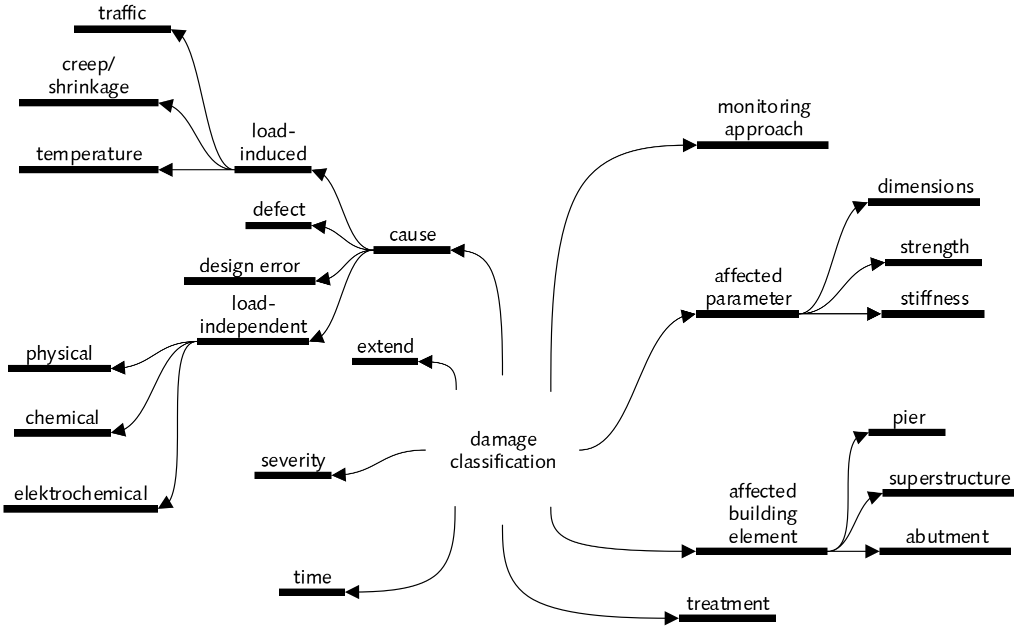

Figure 11: Grouping of different damage information i.e. attributes used for a classification. Completeness is not guaranteed here.

The most obvious classification concerns the type of damage. In [47] their frequency and significance based on statistical data provided by the Thuringian Department of Building and Transportation is assessed in first place. Here, defects are grouped by the affected components which is unfavorable for a formal naming of categories, properties and relations, the basis for a hierarchical structure. Hence, a semantical grouping is proposed instead. Hüthwohl et al. [48] base damage types on inspection guideline requirements and reviewed various codes to derive individual properties of damage kinds. They identify the need to group several types since they do not occur separately. Note that the latter is in accordance with the considerations of degradation processes from the previous section. However, they already identified the deficiencies and stated that “the resulting summary is vague and possibly not sufficiently precise for a structural engineer because the existing inspection documents are already vaguely formulated” [48, p. 5]. A different approach by Hamdan and Scherer [49] did not propose any classification but pointed out that a generic formats as targeted by damage information models needs modular extendibility for any classification. Aiming in this work for an integral solution conductive to structural analysis, it is preferable to categorize damage according to the current phase of the degradation process. Working with inspection data this is inherently difficult since the condition of damage is tracked in larger time intervals and the phase can only be determined by visual appearance. Nevertheless, a damage element has to be linked to an inspection at least to allow a timewise grouping. A degradation process could be represented in this sense by multiple damage record instances aggregated in a specific damage or deterioration model. As an important element time variation is identified in almost all of the related works [47]–[49], [51], [52], but no attempt is made to relate the records to the current phase of a degradation process. Instead, damage records are related to the inspection report with its various sources of information like images, protocols and sketches. Thereby, progress is made in transferring the content from only human to machine-readable formats. For instance, a note from an inspector saying that a significant crack was found on the south corner of a cross-beam needs to be expressed with a discrete reference to the affected structural element and a crack position. In this context, geometrical and semantical relationships are considered which creates some difficulties. The question arises how to represent and visualize the damage geometry, in particular, the extent and its shape. In [49] a layered structure is developed. The top layer consists of the affected building element(s), on the intermediate level the affected region is discretized with a surface, section or volumetric cuboid and on the bottom level the shape, e.g. of a crack, can be described. As stated in the previous section, especially the first and second level are important for structural analysis. A similar idea is proposed in [53] and so called damage cubes are used to represent the changes in structural behavior for failure assessment. However, the geometrical description of the extent needs standardized methods, e.g. on how to carry out the measurements. Since this aspect is not part of current design guidelines [48], research is needed here and again solely the visual appearance might be insufficient for specifying the extent. Hüthwohl et al. [48] therefore primely describe the extent with specific property values like the crack width that can be measured unambiguously and supply the position and geometrical information only in terms of a surface feature, i.e. a mapped texture onto a building element. This way, the geometrical shape is not included and complete modelling of the extent needs to be carried out in an additional interpretation step of structural analysis. Concluding, geometrical and time dependent modeling of structural damage is an open topic and the presented solutions need to evolve further. To summarize the consideration of the current section, a point-and-line diagram is developed in Figure 12. Other attributes for classification like a severity rating or a suitable treatment can be derived from Figure 11. Here, a much simpler implementation using property sets might suffice [48], [49]. In the end, a framework for damage documentation and analysis is targeted. Compared to the current approaches specified by guidelines it is well-structured but limits the flexibility in the description of damage as well [48]. The latter points out a crucial element of a fixed data structure. All concern that are important to structural engineering, operational management or investors i.e. the complete domain need to be analyzed before the software design and architecture is set. Since this represents an intractable problem, modularization is a key element here.

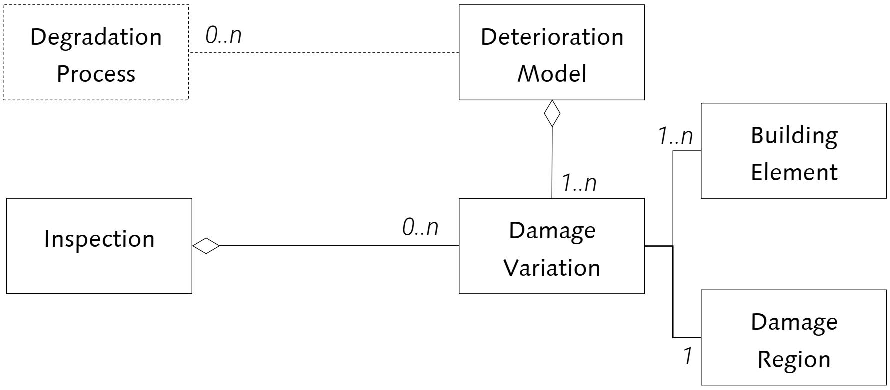

Figure 12 displays a damage information model developed according to the presented considerations. The central element is a registrated deterioration that can be subjected to different degradation processes but could be also a load-induced damage. From the outcomes of an inspection a corresponding damage variation is set up that is linked to the affected building elements and has a geometrical representation. This way, tracking the damage propagation based on different inspections is possible which could result in an association of the damage variation with a degradation value describing the time dependent damage progression and allowing a prediction of the structural behavior.

4.3 Information Management of Building Inspections

4.3.1 Data Models

The information and activities of building inspections presented in the previous sections have to be formalized in a consistent data model. As can be seen, heterogenous input data is acquired by inspections, sensors, photogrammetric reconstructions or laser scans which is then processed to identify and assess damage. A similar variety in data formats is required by the back-end tasks like structural and reliability analysis, maintenance or cost calculations. In between, the data has to be structured, prepared and linked to support this high level of interoperability [6]. This work does not aim for developing such a model since a suitable model is already being formulated at the Chair of Modelling and Simulation of Structures of Bauhaus-University Weimar [5], [6]. Nevertheless, this approach and further possibilities are presented in the following to allow an integral view of the targeted workflows.

In the SEEBRIDGE [54], [55] framework a BIM model based on IFC is proposed for information storage. The idea is to semantically enhance the model in separated procedural steps which can be heavily summarized as as-build model retrieval, preparation with domain-specific knowledge and damage information attachment. The key idea is that only the results of a task are stored in the database which implies that the raw data like point clouds or imagery is not preserved directly or in a linked form. This way, a rigid workflow is established since information is only generated and supplied for previously identified tasks. On the other hand, specifying requirements on the interfaces between activities is a key element of a practical implementation of interoperability and a forward-looking attempt is made in the publications with a proposed IDM and MVD for bridge inspections. However, making the source data available for processing tasks such as automated object recognition [18], image analysis for feature detection [56] or geometrical change monitoring [57] is needed for a design targeting variability. As investigated by Taraben et al. [58] preserving the original data in the IFC rapidly leads to non-processible models and file links are proposed as an alternative. Since point clouds and images cannot be linked to building elements individually, a grouped assignment can be alternatively created. Taraben [6] developed a model container based on the *multi model approach* [59] that manages source data, in particular, abstract and real model geometry with timestamps using concepts named boundary links and snapshots. Boundary links refer to a geometric subset sectioned by an arbitrary shape that can be related to building components for further processing. A snapshot presents a similar concept but in terms of time frames. This way, a requested collection of building records can be supplied to the user. Since the current implementation does not allow a data transfer to interoperability formats used in the building sector like IFC, special interfaces to analysis tools are developed instead. Overall, the front-end resource management is defined in this proposal. Further, building and damage information models bind valuable domain-specific knowledge in an intermediate step before analysis and assessment can be carried out. The importance of this step is easily demonstrated. From point clouds and images only a surface model can be derived which does neither present all bridge components nor a suitable structure to add material and building information or hidden elements. Again, this concern needs another flexible data structure and different approaches exist. Hamdan, Bonduel and Scherer [52] and Kozak and Hamdan [60] proposed *ontologies* to describe damage and bridge components; Ren, Ding and Li [61] used them to describe bridge maintenance. Compared to the hierarchical structure of IFC which supports objects, relationships and properties, an ontology encompasses similar principles but expresses interdependencies in properties and relationships as well allowing significantly more inferences on the domain [20]. Further, axioms, i.e. rules, equivalent to exchange requirements of an IDM can be defined and applied on individuals of a domain to check if they are correctly modeled, e.g. a bridge shall always contain a deck [20], [60]. Since no geometrical information is contained in the current proposals but a linked data approach is presented, the format is more flexible enabling documentation and assessment of buildings even without a complete BIM Model [52]. Especially, the availability of digital 3D representations of existing infrastructure is limited, and as described in section 2.1, its subsequent generation is laborious work. Hence, an ontology combined with a surface model could present enough semantical enrichment for several analysis tasks, e.g. enable the prognosis of the damage propagation without FE calculations. Nevertheless, for a design transfer to structural analysis a consistent geometric definition of all structural members, i.e. full model logic [17] is required which is up to date only achieved by manual created models. In this context, a BIM model, for example in the IFC format facilitating interoperability, seems to possess the best capabilities to represent all needed information for the targeted back-end analysis. As described in section 3.4.3 and 4.2 also a processible damage model in this context consist of a positioning and geometrical description of the extent referenced to the affected building element. In [54] it is noticed that here a different geometric definition of building components using BREP is favorable which is not necessarily compatible to design transfer entities and two individual representations are proposed. Up to the authors knowledge, it remains an open question how to generally transfer damage information from BIM models to structural analysis. Concluding, structural building information currently has to be supplied by an external source and surface features have to be processed and prepared in damage models for structural analysis.

4.3.2 Discussion

Until now, all information is related to the as-is state of the bridge documented by visual inspection and as identified in some of the related works [52], [54] a BIM model is unlikely available as a further data source. Of course, relevant structural information is filed after completion at the responsible authority but it is scattered over multiple blueprints and documents. Further, the question arises if the available documents match the as-build state. Building elements that are hidden to the eye like the reinforcement layout are difficult to verify but are essential for an accurate assessment of the load-bearing capacity or the application of degradation models. As already stated, this problem is identified in the building sector and BIM shall help to overcome it. On the other hand, also the latter might not ensure consistent information which demands some flexibility. For example, a possible scenario could be that the BIM model is poorly maintained but a structural analysis model is available for reuse. In total, only a reliable model allows the application of refined methods. Uncertainties need to be evaluated in the first step and the assessment method has to be chosen accordingly.

The workflow presented in the following and depicted in Figure 13 targets flexibility in the sense that structural analysis entities can be supplied in first place and damage information is transferred in a separated stage. Thereby, simple meaning only geometry and topology as well as refined models supporting reinforcement layouts, different element and material formulations shall be possible. In particular, sensitive regions of a bridge can be refined while others are modeled with coarser elements or approximated. Thus, various assessment methods are enabled. The importance for damage evaluation is illustrated with two deviating proposals. McGuire et al. [53] propose a simple workflow tailored to the examined bridge that transports the cross-section geometry along with damage information to their analysis framework. Damage is then assessed using recalculated section properties of predefined bridge girders. They already identified the additional workload of such a custom-tailored model and stated that “improvements must be made to the interoperation between BIM and finite-element, structural analysis, and/or load-rating packages” [53, p. 8]. On the contrary, the structural analysis model created for design could be reused for damage assessment if the responsible engineers decide that it fits their needs. Taraben and Helmrich [62] implemented the latter using the model container presented in the previous section. In a first step, they used the point cloud to extract geometry information that can be used to calibrate the model and identify a governing load case. They are also able to link damage on finite element level, however, only in a visual form, so that the user decides manually which structural parameter is affected. This step is semiautomated in the proposed workflow. Since damage information is not only interesting for structural analysis but the whole domain of bridge life-cycle engineering, it shall be referenced to the BIM model in first place as an interoperability platform for multiple stakeholders. This way, requirements on the data format and transfer as defined in the SEEBRIDGE approach can be considered. In the next step, the damage classification is then interpreted and transferred to a format conductive to structural analysis i.e. damage is parametrized according to the representation in the BIM model and incorporated in the structural analysis model. Additionally, this approach enables the interpretation of damage information from various sources. They are not necessarily derived from the point cloud or detected features in the model container but could be user defined as well. An additional element that can be implemented here are models simulating the degradation process e.g. a linear reduction of a prestressed tendon area over time. The deterioration value can be directly linked to the considered building and damage element in this case and a corresponding parameter (tendon diameter) in the structural analysis model is set up. Consequently, a damage element always has two representations: one for building and documentation tasks and another specifically developed for the analysis. This implies of course increasing workload but also generality and flexibility of the workflow since it can be adapted to fit the assessment approach. On the other hand, this workflow is specifically developed for the transfer of damage data, but as demonstrated in [5] and [62] meaningful information for structural analysis can be derived from the point cloud as well. Especially, if sequential records are available, governing load cases for quasi-statical impacts can be derived. In this case, deformed states are assigned to model which needs a completely different approach. It is beyond the scope of this work to extent the workflow in this direction. Concluding, a pipeline for building as well as damage elements to structural analysis is presented (see Figure 13).

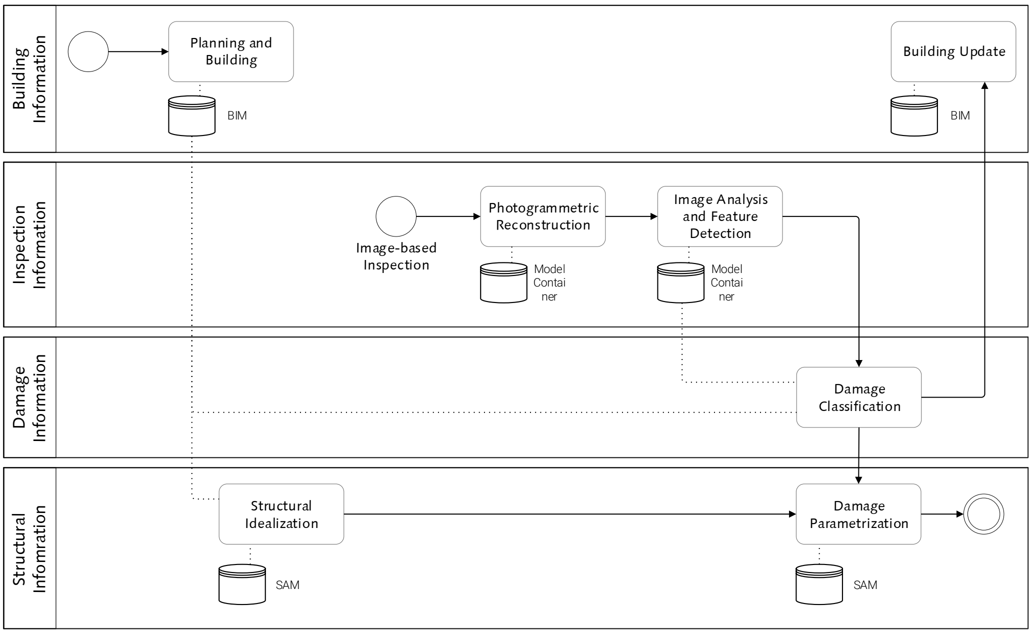

Figure 13 depicts a process map of the targeted workflow using the Business Process Modeling Notation (BPMN). Two sources of data are presented. A BIM model is generated in the planning and maintained during construction so that it represents the as-build state. Secondly, photogrammetric reconstruction and image analysis allow the position and classification of damage. Here, referencing to entities of the BIM model are possible and an enriched building model is derived. In a separated stage, a structural analysis model (SAM) is derived by an automated idealization process. Its structural members have corresponding entity in the BIM model which enables referencing and interpretation of damage elements processed by the analysis tool.

5 Automated Model Derivation in Structural Analysis

5.1 User Requirements

Structural idealization was introduced as model preparation but it can also be seen as the derivation of the *structural analysis model* from the *architectural model*. The latter is nowadays often available in a BIM conform format in an early stage of design facilitating the idea of transferring common entities such as geometry automatically. The process is not as rigid as it might seem. In a building project, stakeholders with different software maintain and develop both models simultaneously meaning that design adjustments or results, e.g. the reinforcement layout needed to be exchanged in various project stages. Apart from this collaboration challenge, difficulties in the derivation process were already named in chapter 3 and can be transferred to functional requirements on automatic approaches. The main user requirements from the point of structural analysis are specified in the following.

- ***Individual Assumptions:*** the derivation program shall encompass freely modifiable interpretation steps to allow different structural idealization strategies. It is advantageous to document the user's assumptions.
- ***Partial Models:*** the derivation program shall be able to split the model into areas of interest or cut-outs to allow a separated analysis.
- ***Model Refinements:*** the derivation program shall allow different levels of refinement meaning that discretization with different element types or material properties is possible. The refinement shall be applicable to any element or region.
- ***Transitions:*** the derivation program shall provide modifiable methods to couple elements respecting their compatibility and the force transfer.
- ***Material Models:*** transferring material data and the enrichment with structural relevant information (from external sources) shall be possible.
- ***Load Models:*** load model derivation from architectural entities as well as external references shall be possible. (not further assessed in this work)

It can be seen that model derivation cannot be isolated from the analysis approach, effectively, it is already contained in the derived structural analysis model. Hence, the dedication of the model is already fixed by the engineering choices in the interpretation steps and only a certain amount of flexibility exists in changing the analysis domain. For example, the overall topology is set but changing constraints is still possible. As such, an automated transfer process is only meaningful if the user can interfere and adapt the routine to her needs. Software vendors as well as researchers have developed different solutions. A selection is assessed with the given user requirements in the following sections. As already stated in chapter 2, standardization in exchanging structural analysis entities is targeted with the IFC ST-4 project. However, it is not achieved up-to-date [63] but used as a promising basis in some of the approaches.

5.2 Approaches

5.2.1 Direct Methods

Analyzing a specific element, e.g. a welded connection, direct meshing methods can be applied. Here, the geometry from the architectural entity is used to generate a mesh automatically for FEA without any intermediate step. Sometimes, exact representations like round-offs are simplified to reduce the resulting mesh size called defeaturing (using isogeometric analysis this step is not necessary). An advantage is that building models are not required to contain any topological or structural information, a mesh can be generated from any solid representation. Hence, a derived structural analysis model is not necessary and the architectural model can be used as the only source of geometrical information. In recent publications [64], [65] this approach is used for the analysis of heritage structures but also in bridge engineering [32].

Also, software tools like ANSYS [66] provide an interface to CAD in this sense. Barazzetti et al. [65] reported some of the faced issues that can be summarized as the extensive work required to defeature the source model and prepare it for structural analysis. Attention has to be paid on geometric continuity (mesh compatibility) the correct modelling of joints, referencing of loads and a sufficiently fine mesh to prevent locking i.e. an incorrect bending compliance. On the other hand, the mesh needs to be coarse enough to remain processible. Further, internal forces are not directly derived, instead design targets need to be defined to allow postprocessing [32]. At the end, it is possible to obtain a very accurate simulation but it requires meticulous work despite automatic meshing. Daily problems of designing reinforced concrete structures and even bridges do not require such accuracy but a simplified and manageable structural analysis model [28], [67]. In structural engineering, this approach usually does not present any time savings and its usage can only be justified in cases where accurate simulations are needed. However, the reader should note that volumetric representations are gaining popularity in the context of life-cycle analysis with nonlinear FE models [40]. The software ATENA [68] is a good example for this having an interface to a universal pre-and postprocessor GID [69] providing import and export capabilities of CAD geometry.

5.2.2 Abstraction of architectural entities in a semi-automated process

The development of a structural analysis model requires some abstraction steps where structural entities are reduced to their mechanical problem. In this sense, beams and columns are represented by their centerline and walls and slabs by their reference plane, often called *wireframe models* illustrated in Figure 14. Reasonable simplicity and accuracy are achieved naturally and hence this highly popular approach is up-to-date taught and used in universities, engineering offices and research. Also, BIM centered software like REVIT [70] and the interoperability format IFC adopt an analytical view on beams and slabs and enable structural design in this way. REVIT automatically creates the analytical representation from architectural entities and allows its modification and transfer to calculation tools like SOFISTIK [26]. Considerations on the effects of displaced centerlines and contact areas are possible but, as already stated, attention has to be paid to the discontinuity regions and transitions. The joint of a beam and slab element with a node-to-node connection will likely produce a singularity and the resulting values cannot be considered for design. Even though such details might be assessed separately they illustrates the shortcomings of the presented approach. On the other hand, a substantial degree of freedom in modeling exists despite the automatic generation. It can be adapted to boundary element representations [71] or used for bridge design to a certain extent [72].

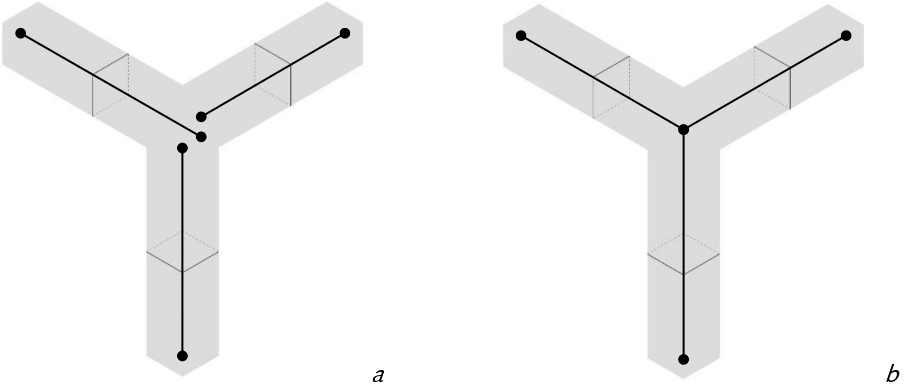

Figure 14: A typical frame corner that is modeled using beams with an extruded square cross section along a central axis. In (a) the architectural representation is given where connectivity is only assured with touching end faces. In (b) a structural representation is given. Here, the topological relationship is clear since the centerlines meet in a common structural node.

Flexibility and adaptability can be enhanced with the ability to interfere with the generation process. Often, software solutions provide an application programming interface (API) that provides access to chosen entities and methods of the system. This way, architectural elements can be subject to an abstraction process and transferred to structural analysis establishing a specialized and proprietary workflow. This approach is platform dependent and thus hardly generalizable. Understanding the software system and a certain amount of programming skills are needed as well. However, visual programming tools like DYNAMO [73] enjoy increasing popularity in the field and can present a flexible environment for the data transfer (see [74] for the export of bridge models using the IFC 4.2 MVD and DYNAMO). Another framework is provided by the IFC itself. It is an open format that supports architectural and structural analysis entities equally. Many open BIM toolkits like APSTEX [75] or XBIM [76] allow easy modifications and can be used for a transformation of the architectural to a structural definition, e.g. the bridge geometry from a BIM authoring software can be made available for calculation tools if both parties provide an IFC interface (see [77] for a review). But functionality of this method is only given if the geometrical information contained in the IFC allows structural interpretation. The IFC scheme allows various geometrical representations. For example, a steel girder could be stored using a BREP or an extrusion whereby only the latter facilitates the extraction of the centerline and cross-section. Since BIM authoring tools are usually based on object-oriented modeling and information exchange via IFC, implicit geometry representations are usually the case and consequently a meaningful concept is presented. Developing a system that provides transformation routines - especially ones that enhance the model's topological relationships - can simplify the exchange process to a major extent. Making human reasoning about spatial relationships and domain-specific knowledge available in machine-readable items is the key element here [78]. To illustrate, the topology given in architectural models is compared to a structural analysis representation in Figure 14. A systematic approach would then identify these areas based on the geometrical connectivity and make the implicit information explicit i.e. create a structural node that is shared among the connected beam elements. As proposed by Sacks et al. [79], [80] or Ramaji and Memari [27], [81] a standardized scheme is possible. The idea is to collect a domain-specific *inference rule set* and use it to interpret and enhance the semantics of a model in a given transfer context. According to their considerations, information exchange can be divided into two categories: direct and interpreted information transfer. The transfer is itemized i.e. building entities are separately processed and only the required items are modified. Provided is an underlaying "library of concepts, properties and relationships, geometry and spatial orientation operators, spatial topology operators and auxiliary operators", as stated in [80, p. 266], that are executed in the inference rules. The advantage is that such operators can be used in a systematic manner without extensive programming skills. Only condition statements (IF-THEN) need to be set up. Further, rules can be based on another and executed in successive iterations to allow more complex transformations [79]. Altogether, a user-controlled derivation strategy can be implemented. Critically reflected, such transformation based on IFC are only developed since BIM centered tools have not implemented MVD matching import and export strategies as interfaces to domain-specific analysis software [27]. Nevertheless, the present concept has a huge potential and can be also incorporated into BIM tools as a semantic enrichment engine from and to native data format [80]. Unfortunately, the current implementation SeeBIM 2.0 [82] misses some basic auxiliary and geometric operators, e.g. get the intersection point of two lines, for the model transformation to a structural analysis view. Up to date, only creating entities of IfcElement and IfcRelationship are possible but creating vertices or edges of IfcRepresentationItem is essential in this process.

5.2.3 Parametric geometry definition as a common data structure

An elegant way of exchanging geometry is to find a common definition and exchange only this information. Especially, in bridge design *parametric modeling* is a practical approach to describe the geometry. Attributes of building entities such as height, width, length which can be either defined with fixed values or variables, i.e. parameters are composed in algebraic and geometrical-topological relationships to form a geometrical representation [14]. In a sketch-based approach points and lines are constrained by defined dimensions and topological considerations like fixed positions or parallelism that are understood by the solving system to build the sketch [14]. Apart from the advantages for design already named in section 2.1, parametric modeling is extremely interesting for the data exchange out of two reasons. First, the set of parametric definitions is clearly manageable and the implementation of the transfer routine straightforward. Second, not the design result is transferred but the design intent meaning that functions, e.g. describing the optimized height distribution along the main axis are preserved [67]. Hence, the engineering choices are contained in the model and little effort is needed for the derivation. Due to the different design philosophies of architectural and structural modeling, interpretation steps are nevertheless needed which can be easily demonstrated with the double-T-beam bridge example from Figure 1 to Figure 4. Further, the designer might consider which parameters are actually meaningful. Describing a detailed geometry fully parametric can lead to overwhelming and non-transparent models. From the perspective of structural analysis, however, cross-sectional parameters or the position of the piers implemented as variables simplify early design iterations to a major extent [67].

A prerequisite of this method is of course that the BIM authoring and the structural analysis tool support parametric modeling. Then, either a platform-depended or an open transfer process can be established. Ji et al. [14] introduced a sketch-based parametric concept in the IFC Bridge project and demonstrated its efficiency with two workflows. However, despite the advances made with the IFC 4 design transfer view, parametric concepts are not fully incorporated [17]. A proprietary workflow on the other hand is much easier to set up e.g. with a DYNAMO package [83] that provides basic functionality for a bidirectional link between parametric bridge models in REVIT and SOFISTIK.

5.3 Comparison and Evaluation

Three different approaches are presented in the last sections. Since implementing all possibilities is beyond the means of this work, the aim is to select the best fitting one and adapt its ideas. Their individual characteristics were already described in the previous sections. Now, the user requirements defined at the beginning (section 5.1) are taken for assessment of the derivation processes displayed in the column headers in Table 2. Such an multi-criteria decision-making technique can help to compare alternatives systematically; of course the given scores introduce a significant degree of subjectivity and the result should be critically reflected [84]. The reader should note as well that only general structural analysis criteria are reviewed so far. Depending on the situation, for example introducing such automation in a company, might demand specific derivation strategies that would result in a completely different implementation. On the other hand, targeting interoperability and standardization all three should be incorporated. Due to the additional focus on damage modeling in this work, the conclusions on modeling of defects from section 4.2 shall be considered. As already stated, it is advantageous to decouple structural analysis derivation and the damage attachments to the model. The derived model needs the same capability to add damage information as the source model in this sense. Hence, in the decision-making process a further criterion is introduced which is given a higher priority (see weight distribution in Table 2). Further, damage can be modeled using different FE strategies as can be seen in section 3.4.3. Depending on the approach their applicability is limited. For example, a parametrized bridge deck will need a revised model logic in order to reduce the height in only a specific part of the section. Using a volumetric representation, a parametrized subtraction solid needs to be defined. Especially, the latter requires suitable formulation possibilities of the used transfer file format; here constructive solid geometry (CSG). Hence, the feasibility of the file format has to be assessed as well. Due to the discussions on the integration of the targeted workflow in the overall domain in section 4.3, the comparison in this section is limited to file formats used in the building sector or proprietary transfers. In total, this work aims for a first approach on generality of damage information transfer and a satisfactory analysis cannot be guaranteed for all cases. The selection of the user requirements captures the latter to a certain extent.

Since different methods using the same approach where assessed in section 5.2.2 the target has to be specified again. The concept of an inference rule set seems very promising. But as already identified, the current available frameworks are not elaborated enough to allow the necessary transformations. To supply basic operators spatial queries as described by Borrmann and Rank [78] are needed which are usually provided by the API of BIM centered software or in the XBIM Toolkit (XbimGeometryEngine). Out of this availability, the general concept of inference rules independent of the implementation is used for the comparison. The same can be said for direct transfer and parametric models. Finally, the result from decision-making matrix (see Table 2) show that the systematic approach using inference rules is clearly preferable. This supports the reasoning from the previous sections as flexibility and adaptability are conductive to the generation process.

Criteria	*Individual Assumptions*	*Partial Models*	*Model Refinement*	*Transitions*	*Damage Models*	
Weights	0.3	0.2	0.15	0.05	0.3	
Direct Method	0	2	2	1	2	**0.68**
Inference rules	2	2	1	2	2	**0.93**
Parametric Model	2	0	1	2	1	**0.58**
	2	2	2	2	2	1

Table 2: Multi-criteria decision-making technique adapted from [84] is applied for the comparison of the presented derivation approaches. Individual weights for the user requirements are assigned and the approaches are assessed with scores raging from impossible (0), difficult (1) to simple (2). The end score is given in the last column after normalization.

6 Implementation

From the groundwork of the previous chapters it becomes apparent that a wide spectrum of possibilities to identify, classify, model, analyze damage and its related process exists. A similar variety can be found in the structural analysis representation and model derivation of buildings. Hence, customized and highly specialized solutions, especially in structural health monitoring, are currently available that use only a subset of the design and analysis possibilities. On the contrary, this work targets are more general framework that enables different analysis and modelling scenarios with various tools. A widely used interoperable data format is the foundation for this and hence the implementation is centered around IFC as explained in chapter 2 and section 6.2.3. However, due to the recent release of IFC4X2 and the omission of the structural analysis view in this draft, restrictions exist [17]. In general, this work aims for a prototypic application that reduces complexity by concentrating on specific derivation methods further described in the next section. The top priority is to demonstrate the potentials and limits of such a workflow. As already stated in chapter 5, a program using interpretation unit steps and inference rules is targeted. From this point of view a structuring in domains (areas of knowledge) and in processes (pipelines) is advantageous. This allows to consider always a subset of operations on a specific stage i.e. model that can be summarized in an interpretation task. In particular, the identified core feature are the four stages and three interpretation processes depicted in Figure 15. The surface model and damage data base are not part of the implementation as described in section 4.3 but present one of the main inputs. The other available information source is the bridge design model in the IFC4X2 format. Up-to-date, no description of the Design Transfer View MVD is available on the BS website [16]. Hence, a suitable representation is assumed further described in the following section 6.2.3. Additionally, a flexible configuration of the tool is enabled, e.g. the user can alternatively start with the structural analysis model right away. Further considerations from structural and information modeling are assessed as well. To highlight, the domain analysis is carried out in the groundwork section. The domain design is briefly described in the following but the reader is referred to the repository for further information. It is based on the IFCRAIL branch of the xBim Toolkit [76].

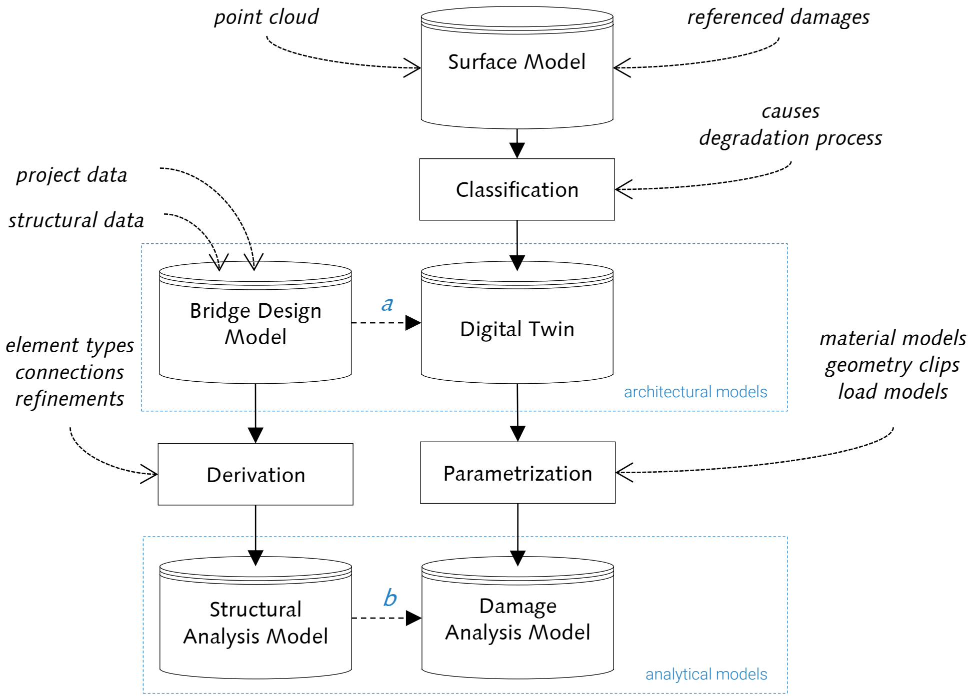

Figure 15: The approach is summarized in the two main workflows - structural analysis model derivation and damage information processing - and their interfaces. Four model stages highlighted with the data base symbol referring to their storage in a corresponding IFC file and three main processing tasks – classification, derivation and parametrization - are identified. Link (a) and (b) refer to the alignment-based positioning.

6.1 Concept

The main work of the implementation elicits how the four model stages should be designed to enable and support the processing tasks. The main ideas behind the implementation are derived from an exemplary damage analysis workflow described in the following, depicted in Figure 16 and in accordance with the first considerations on the domain in Figure 15.

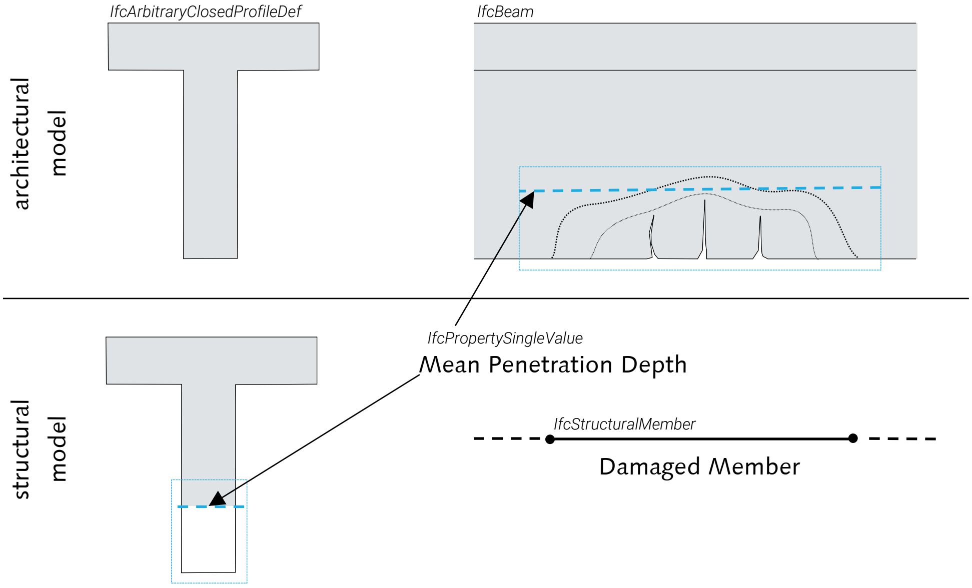

Figure 16: Exemplary process of interpreting and transferring a damage information item to structural analysis. The damage variation of a deterioration model is represented by a bounding box which is used as a clip on the member's cross section to implement the damage.

A suitable double-T-beam exemplary bridge in the format of a *Bridge Design Model (BDM)* is generated in the IFC 4X2 format. In this model, the alignment and the cross-section geometry at specific stations (curve parameter) is available. All bridge elements like girders or piers are positioned relative to the alignment. An interpretation process transfers the bridge elements then to the *Structural Analysis Model (SAM)*. As described in section 3.1 and 6.2.2, secondary alignments are created and structural members are positioned relative to them. Operations on the cross-section are needed to split it into two parts. At the same time a digital twin inheriting the classified damage from the surface model is prepared. Deterioration Models further described in section 4.2 and 6.2.1 contained in this *Digital Twin* are again relative positioned to the alignment from the BDM depicted in path A in Figure 15. This is a key element in the derivation process since a traversal along the alignment used for the superstructure positioning enables the selection of the affected cross section entity at the positioning station in the design model. For the beginning, their extent measured at a certain damage variation is modeled as a bounding box and a mean penetration depth is given as a parameter if a chemical degradation process was identified (see Figure 16). This way, a parametrization and implementation in the SAM is enabled. The section of the bounding box is used as a clipping geometry on the cross-section of the structural member. Finally, a damaged member over the length of the extent using the latter replaces the present member in the SAM illustrated via path B in Figure 15. Other representations are possible as well refining the damaged member using further element types like plates or slabs. The clipping procedure can be applied and refined as a polygonal boarded region of the surface and the thickness is adapted according to the damage extent. Since the extent can increase from each damage variation to the other, the implementation in the SAM up-to-know represents only the condition related to a certain time instance. A parametrization can be achieved if the degradation process is available as a function. Ideally, the function can be calibrated with the observed mean penetration depth. A structural engineer could use this information then to simulate and prognose the future load-bearing behavior. Since the concept of functions and parametrization is up-to-date not implemented in IFC the static representation of a chosen time instance has to suffice for the beginning.

6.2 Domain Design

6.2.1 Information Modeling Requirements

The characteristics of degradation and damage processes, their classification and modelling are assessed in section 4.2. Now, the knowledge gained shall be implemented in the IFC4X2 scheme using the build-in extension mechanisms i.e. proxy elements and property sets (see Figure 17). This has the advantage that no changes of the scheme are required and standard software allows a visualization of the bridge including the damage information items. On the other hand, the implementation is limited to the existing entities and relationships and some drawbacks have to be accepted described in the following.

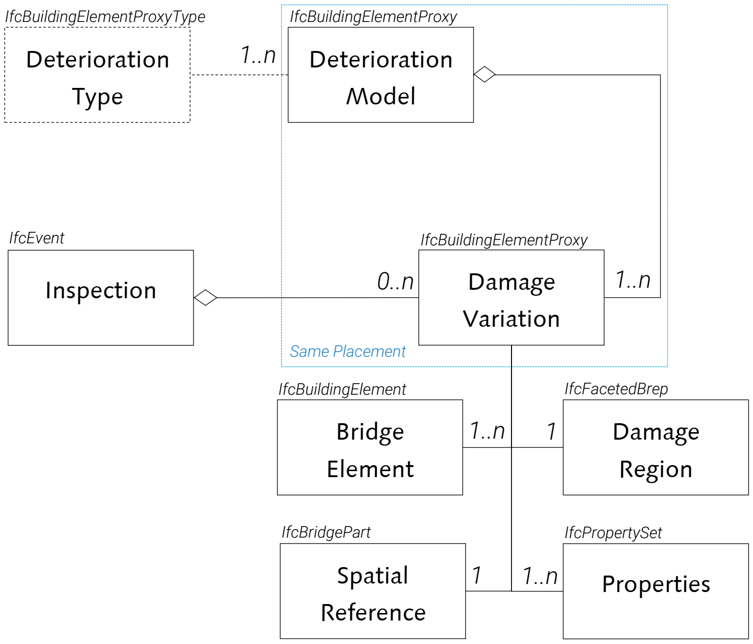

Figure 17: The structure of a deterioration model grouped in the damage information model is shown. It is decomposed by of 1 to n damage variations and has an assigned type. The variations can be ordered in time via the assigned inspection. Reference to the spatial context and interference with building elements is established with relationship entities.

In Figure 15, the corresponding model stage is called digital twin referring to the idea that a representation of the as-is state in IFC is possible. Here, only a part of this model the *Damage Information Model (DIM)* is considered. Starting by tracking an individual damage a *Damage Variation* is created as a proxy element and aggregated in a *Deterioration Model* as the summarizing proxy element. Damage variations are always positioned relative to the deterioration model. The position of the latter is measured along the alignment if the superstructure is affected. Otherwise, it is locally placed in the spatial context of the piers or abutments. This has the advantage that the positioning relative to the affected *Bridge Elements* of the BDM is implicitly given and the impact is not limited to a single element. A traversal along the alignment allows then a computation of the spatial overlap. The recorded extent of the damage variation can be represented in different ways. As a basis, a bounding box enclosing the *Damage Region* is sufficient. For transferring the actual geometry, e.g. spalling body, an inference relationship to the bridge element is proposed including the inference geometry as a curve, surface or volume. Compared to pure surface references, a damage geometry is made available and a damage region defined. Additionally, the advantages of the IFC objectified relationships are used to enable a classification using the spatial context as well as the affected building elements. Timewise grouping is possible using an assignment to the

Inspection which is modelled as an event with a time stamp inside a maintenance process. The next inspection will add a damage variation with possibly diverging properties to the deterioration model. Up-to-know only the effect of the damage process is given and no cause related. Thus, a *Deterioration Type* from the proxy element type class is introduced to specify the category of deterioration, e.g. mechanical, chemical or physical, and describe a degradation model in this sense. Information about the type can be refined and characteristics of the model described in property sets. This way, also a series of degradation mechanisms can be assigned using different types. However, the IFC scheme lacks concepts of parametrization and no function describing the degradation process can be created. Out of the same reason, damage variations cannot be linked to a progress value in the corresponding phase of degradation. Here, a workaround using property set templates or an external reference is proposed. A template added to the damage information model summarizes all stages and an enumeration value inside the properties of the damage variation points to this table. Reading this table in an interpretation task allows an estimation of the damage progress and the material properties or reinforcement diameters can be adapted. For such a workflow, characteristics of degradation processes have to be known and manually added to the deterioration model during classification. Up-to-date, they are not completely standardized but libraries exist which could be used for the latter; often given in reliability-based design guidelines [50], [85] and software [86]. A good summarization can be found in [37]. However, for a proper transfer parametric definition and an MVD for reliability analysis have to be added to the IFC scheme. Also, structural analysis software could profit in many ways from such an exchange as stated in [87], especially if degradation processes are transferred, as most tools do not provide a library for such an analysis.

6.2.2 Structural Requirements

Structural idealization is a highly individual task in the responsibility of structural engineers. As already stated in section 2.2, the IFC scheme therefore provides elements for wireframe and surface representations decoupled from the commonly shared building elements. In this sense, a structural analysis model is viewed as a separated entity to include the mechanical aspects of the building and a corresponding MVD is supplied. As assessed in section 5.2.2, a semi-automated derivation solely based on the architectural representation in the IFC is possible. It is the goal of this implementation to show the potentials of such a workflow in the context of damage analysis. However, the idea of inference rules is neglected and the user is requested to engage with the library for customization. Concerning bridge engineering and damage modeling, new concepts and specialized methods are introduced in the following. Routines to generate partial models to assess damaged regions separately, e.g. of a cracked discontinuity region, are not provided for detailed models. Often volumetric representations are advantageous here which are not part of the structural analysis domain of IFC. Nevertheless, functionality for queries and interpolation of cross-sections are available which enable the extraction of spatial regions without changing the element types. In general, the library is designed for the analysis of the complete structural system and damage interpretation on this level.

Most of the concepts are subjected to the superstructure as the main load bearing and thus usually the most sensitive member. Its is assumed that the alignment is used as its main axis i.e. for positioning and referencing of structural properties. Station values determine the position of cross-sections, supports and also deterioration models. The underlaying curve could be parametrized, a NURBS curve or simply a polyline. For demonstration purposes only polylines are considered. Secondary alignments as explained in section 3.1 are derived as offset curves from the main axis. Structural members then use the latter as a basis curve. They differ from the superstructure in the sense that they present single load bearing members and in combination form its mechanical system. In the case of the double-T-beam bridge from Figure 4, the section is split into two parts where the separated sections consider the effective width and are assigned to the structural member representing the resulting T-beams. A connecting member, i.e. surface or grillage, is needed to model the transversal load bearing direction. Often the girder height is optimized for an efficient distribution of self-weight and load-bearing capabilities. Since parametrization is currently not foreseen if the IFC scheme, cross-section objects with varying properties are assigned to the stations of the girder to include these aspects. In conclusion, a derivation must use a sequence of tapered structural members here and the girder is segmented in longitudinal direction. Additionally, routines to consider support conditions introduce new segments as explained in section 3.3. In particular, the mechanical connection of abutments and piers to the superstructure needs to be modeled. Constraining the degrees of freedom from one structural point to the other for coupling is foreseen in IFC with eccentric connections. Alternatively, a connecting member representing the stiffness of the connection can be created. However, modelling the discontinuity region here is difficult since mixed-dimensional coupling is needed. Such aspects are more easily introduced subsequently in the structural analysis tool where the structural engineer has full control. In total, the routines support the structural engineer in the first steps of the structural idealization process, i.e. to build the first structural analysis model. Refinements shall be carried out subsequently in the structural analysis tool.

More important in this work is the development of interpretation routines for deterioration models. As previously said, it is important to position them relative to the alignment in order to unambiguously interpret the extent. Over the length of the damage region, a new damaged member replaces the existent member. The bounding box is then taken from a chosen damage variation and used as a clipping geometry to include the damage in the cross-section of the member as displayed in Figure 16. The clip, i.e. intersecting geometry, could be removed from the effective load-bearing section or a damaged material is assigned to this area. Using a new material individual parameterization can be retrofitted in the structural analysis tool. This strategy works on arbitrary cross sections. However, their outer and inner geometry has to be defined by polygons. Enclosed reinforcement bars are represented in the IFC as component elements and not necessarily as parts of the cross section. Hence, a separated interpretation method needs to be developed. But as previously stated, it is questionable if such information from the as-built state is available. Nevertheless, prestressed concrete girders must supply at least the tendon elements due to their importance for structural safety and the structure's possibly high sensitivity to changes in prestressing. Weariness, aging and additional degradation processes reduce the prestressing (or effective area) and thus have to be regarded in reliability analysis. In IFC4X2 they are modelled as component elements as well, however, a suitable representation in the structural analysis model is the computation of a corresponding load case (of course, the duct needs to be subtracted from the section). As already stated in section 3.4.3, they thus fall in a special category in damage modeling. A deterioration model shall be created especially for an affected tendon that describes its degradation since the analysis process will be inherently different for grouted or coated tendons. If the structural engineer is additionally interested in detailed modeling of tendon's damaged region or anchoring, volumetric representations are advantageous which are as previously stated excluded from the current implementation. To summarize, a reliability analysis is enabled on the complete structural system. The supplied routines work with beam elements and damage is introduced on a cross-sectional level. In this sense, a first approach to semi-automated reliability analysis is presented.

6.2.3 Interoperability Requirements

In this section, the representation of the bridge in the design transfer view and structural analysis view MVD is assessed. Two guiding figures are provided; Figure 18 and Figure 19. To understand the basic concepts of interpreting commonly shared building elements in IFC the reader is referred to the detailed explanations in [16], [17], [81] used as a reference here. The implementation follows the IFC4X2 scheme as much as possible but some diverging concepts for the bridge analysis model are proposed.

Bridge and structural elements inherit the attributes of *products* which means they are unique objects occurring at a specific location in space and using geometrical or topological items for their representation. Since an alignment-based geometry shall be used, placing objects is essentially different to standard building models. Alignments as positioning elements provide an axis geometry. It can be represented with different types according to the scheme. So far, only polylines, linear segmented curves and offset curves are supported in this implementation but extendibility is foreseen. Alignments can be segmented by station values that are later used for referencing bridge or analysis elements. They are expressed as *referents* in IFC and are used as a wrapping element for *linear placements*, however, the girder body definition use only its distance expression displayed in Figure 18. Components like the superstructure further use the alignment as the main axis. In the same way, derived alignments describe the path of building elements that follow the superstructure in the longitudinal direction like tendons, caps or railings. On the other hand, substructures like cross beams, piers or abutments use the referents for linear placement. The latter was introduced in IFC4X1, unfortunately, most IFC viewers currently do not support this class. An alternative is to translate the linear placement into the global coordinate system. However, the relation to the alignment is difficult to trace back. Preferably, a complete alignment-based positioning is enabled for all building elements.

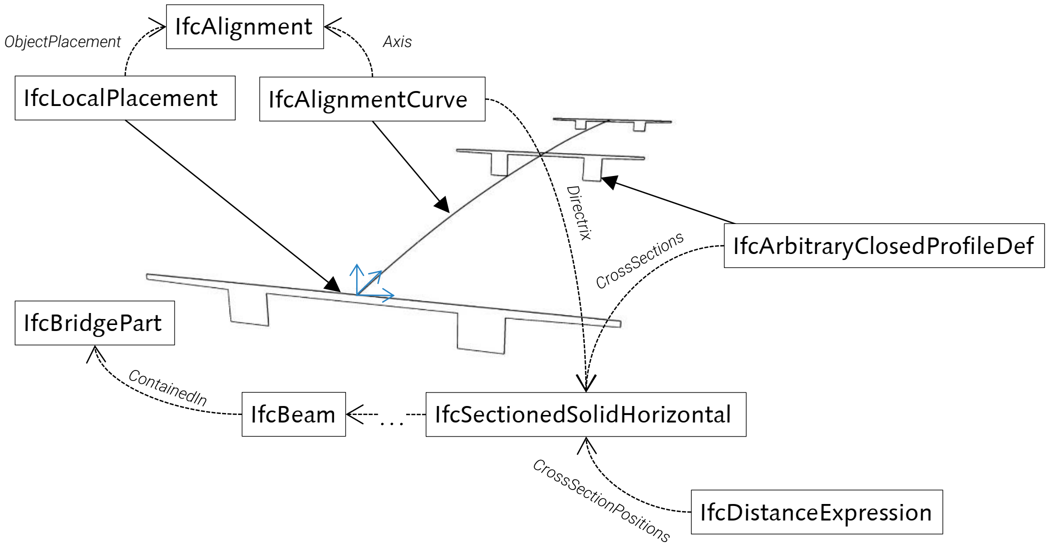

Figure 18: The bridge design model of the sample bridge is displayed using suitable IFC classes. A key element is the main alignment which all bridge elements use for positioning. Here, the bridge body is modelled as a sectioned solid in order to allow varying cross-section measured along the alignment curve using station values.

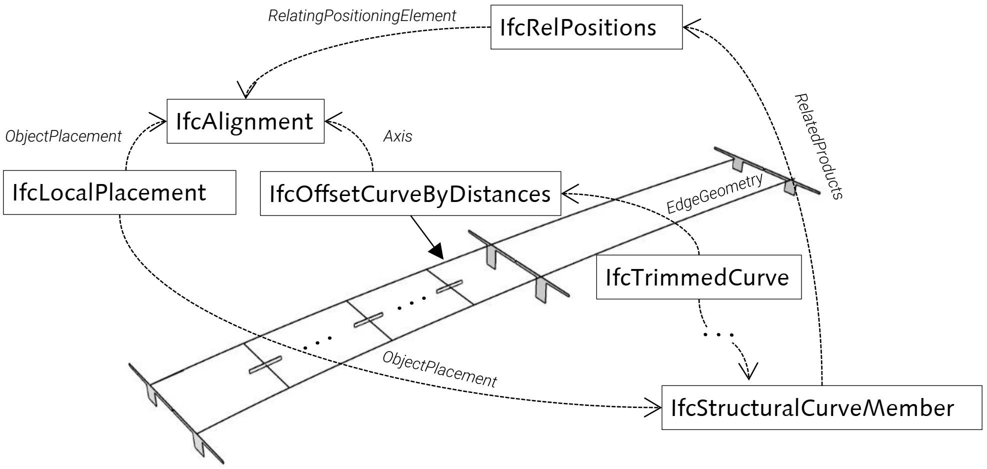

Figure 19: The structural analysis model of the sample bridge is displayed using suitable IFC classes. Structural Member use secondary alignments for their underlaying geometry. To allow segmentation, the offset curve is trimmed. Structural points are positioned on the secondary alignments using station values.

An important prerequisite for the structural analysis model is that the main and derived alignments are always spatially contained in the site and hence create no new coordinate system. This way, structural items are defined in this space and shared connections have a consistent position. For structural points, no concept for the mapping to station values exist in the structural analysis MVD. As a workaround, the *point on curve* and *trimmed curve* class using station values translated to *parameter values* (0 to 1) are proposed for structural members (see Figure 19). Points on curves present only a solution in some cases since offsets cannot be regarded in this class. Hence, transformation to global coordinates needs to be enabled. Unfortunately, only cartesian points are allowed in the standard import to structural analysis tools and a custom routine to transfer alignment-based models to SOFISTIK [26] is developed. As previously stated, a bridge maintenance as well as a bridge structural analysis MVD are required in the long term and alignment-based geometry is a prerequisite here.

The last important elements are connectivity statements and the cross-sections in the transfer. A *connection relationship* expresses the link from points to members and supplies the mechanical boundary condition. This way, also connection that do not share the same point position can be connected and the eccentricity modelled. However, this is then not a node-to-node connection which would be advantageous in bridge engineering. The same concept applies to the connection between members and surfaces. Cross-section and their material are stored in *material profile sets* that can be assigned to bridge and structural analysis members on station level equally. Composition of cross-sections as well as tapering members are possible. In this sense, the damage modeling approach on cross-sectional level can be implemented. The needed functionality for import, interpretation and export is achieved in the implementation via wrapping the entities with a corresponding class on product level. A model explanation on IFC code snippets can be found in Appendix B. From the perspective of interoperability, also the representation of the four model stages in the corresponding MVD have to be regarded. As explained, due to the draft status of IFC 4x2 no explanations of the MVD are given. Further, concepts described in the structural analysis view are violated in this proposal as well which makes its usage needless. In conclusion, a design transfer independent of standardized subsets of the IFC scheme is implemented and the information from all model stages can be also stored in one file. Nevertheless, the introduced ideas specific to bridge, structural analysis and damage modelling can present valuable functional requirements for the future development of a bridge maintenance MVD. But no claim to completeness is made in this implementation and adaptions might be needed.

6.3 Software architecture

To understand the idea of the implementation, the software architecture does not necessarily need explanation. However, for its further usage some important aspects are described. The complete implementation is based on the IFCRAIL branch of the xBim Toolkit providing an intuitive .NET open-source library to read, create and view building models in the IFC format [76]. Using a similar software architecture, a .NET C# class library [88] is developed called SIDI (Structural Interpretation of Damage Information) [89] that supplies basic functionality to interpret the model stages. The idea is that an interpretation routine can then be developed by the user. To get started, the case studies created in this work can be found in the repository.

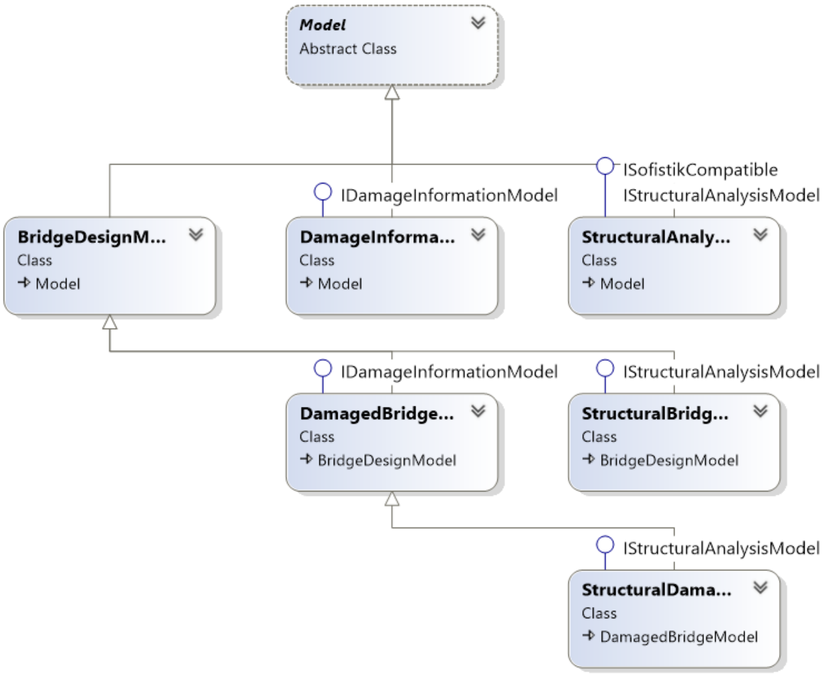

Figure 20: An extract from the class diagram (see Appendix A) shows the three major models that are designed as a factory and observer to create items in the domains. Derived models are supplied to combine the domains.

Since IFC represents a vast field of entities, functionality is not added to single classes but all entities belonging to a certain domain are wrapped up in components. In particular, *Items* and *Models* in order to avoid redundant creation activities. In this sense, uncomplicated IFC read and write functionality is provided. A factory pattern is used to add items in the four major model stages, in particular the bridge domain, damage information, structural analysis and the damage analysis model are only a variation of the previous as explained in Figure 20. The required properties shall be either defined in this step via lambda expressions or derived from the corresponding IFC entity. The models also act as an observer and guarantee their consistent usage via checking the added items for uniqueness and if required updating their properties. For example, a newly introduced structural member will be updated if one of the end points already exists in the model. This way, mechanical connection is already guaranteed if explicitly stated. An eccentric connection, on the other hand, has to be created by the user. In general, only basic functionality and properties are encapsulated. The involved processes as described in the previous sections have to be created separately as executable routines. For further explanation, the reader is referred to the class diagram in Appendix A or the XML documentation accessible via the object browser in VISUAL STUDIO [90]. The guiding example of the double-T-beam bridge and the corresponding IFC files can be found in the repository as well. The basic ideas are explained in the following with code snippets illustrating the generation and structural interpretation of a simple girder bridge. The involved transfer processes are separated into the following methods.

- ***BRIDGE2BIM:*** this method creates the example bridge.

```
var bridge = new BridgeDesignModel(model);
bridge.CreateAndInitProject(model);

// create alignment curve
var alignment = bridge.New<Alignment>(a =>
{
        a.Curve = new List<Point3D>() {
        new Point3D(0, 0, 12000),
        new Point3D(150000, 0, 13995)
        };
});
```

Listing 1: An extract from the process generating the bridge design model is shown here. First, the IFC-Bridge project structure is set up. Then, entities are added to the model; the alignment being the main element for positioning.

- ***BIM2SAM:*** this method derives the structural analysis model using secondary alignments and a connecting surface slab.

```
// traverse all stations and create structural members of superstructure
foreach (int i in Enumerable.Range(1, stations.Count - 1))
{
        // get corresponding girder segment
        var before = girder.StectionBefore(stations[i]);
        var after = girder.StectionAfter(stations[i]);

        // create structural members
        var sm = sam.New<StructuralMember>(m =>
        {
                m.Source = girder;
                m.Stations = (before.Station, after.Station);
                m.Sections = (before.Section, after.Section);
        });
}
```

Listing 2: An extract from a process transferring the bridge design model to the structural analysis model is shown here. The loop creates structural members from girder segments. Here, structural points are derived from the given stations inside the C# property member mechanisms.

- ***BIM2DIM:*** this method adds a sample deterioration model based on two damage variations from to subsequent inspections.

```
// create second damage at linear placement
var dv2 = dim.New<DamageVariation>(v =>
{
        v.Name = "Damage Variation 2";
        v.Inspection = i2;
        v.Deterioration = dm;
        v.Phase = "Corrosion";
        v.Extent = dim.New<Bound>(b =>
        {
                b.Min = new Point3D(-1100, -500, -1500);
                b.Max = new Point3D(1100, 500, 100);
        });
        v.MeanPenetrationDepth = 0.4;
        v.AffectedItems.Add(dim.Girders.First(), null);
});
```

Listing 3: An extract from the process generating the damage information model is shown here.

- ***DIM2SAM:*** this method that processes the structural and damage information and introduces a damaged member at the location of the deterioration model.

```
// clip section
var shift = new Vector2D(deterioration.Station.Value.Y,
deterioration.Station.Value.Z);
var extentin2d = extent.In2D(shift);
var damagedsection =
((BoundedSection)affected.Sections.Start).Clip(extentin2d);

// assigning different material to intersection
var damagedpart = ((BoundedSection)affected.Sections.Start).Clip(extentin2d,
ClipperLib.ClipType.ctIntersection);
damagedpart.Material = sam.New<Material>(m => m.Name = "Damaged 1");


var combined = sam.New<CompositeSection>(s => s.Sections = new List<Section>()
{ damagedsection, damagedpart });
```

Listing 4: An extract from a process transferring a deterioration to the structural analysis model is shown here. The extent is reduced to a 2D section and clipped from the cross section of the structural member resulting in a composite section with two different materials.

In every interpretation task, the domain models are assigned to the IFC model and corresponding IFC entities are automatically read. As can be seen from Error! Reference source not found. to Error! Reference source not found., the user can then start to modify and create new items. After the interpretation process is finished, the model is exported to an IFC file which is read in the subsequent step. As previously stated, the concept of MVD is not applied and only an undamaged and damaged IFC-bridge is created. A second interface to SOFISTIK generating alignment-based DAT-input files is supplied since the standard IFC import does support neither IFC4 nor recreates the alignment-based positioning. Alternatively, for visualization purposes or standard interoperability, the alignment-based positioning can be transformed to global coordinates and written to the IFC file as well.

7 Proof of Concept and Case Study

The main features of the library are demonstrated in this chapter. First of all, the core functionality is tested meaning that each model stage can be written or read from the corresponding IFC file. The interpretation steps in between are then user configured programs in order to allow for different strategies in structural idealization and damage processing. Due to the recent release of IFC4X2, not many example bridges are available none of which uses alignment-based positioning. Hence, the guiding double-T-beam bridge is created using the bridge design model of the library. The steps to derive a structural analysis model are explained in section 7.1. To demonstrate damage processing, i.e. computing a clipping geometry from spatial overlaps, a deterioration with an assigned corrosion process is introduced in section 7.1. A case study in section 7.2 gains damage information from imaged-based inspections of the Scherkonde Viaduct, a semi-integral railway bridge on the high-speed link between Erfurt and Leipzig further described in [5], [91].

7.1 Structural Idealization Possibilities

Considering the domain concepts from section 3.1 and their preparation for implementation from section 6.2.2, the guiding double-T-beam bridge is now structurally idealized in different ways. As previously stated, the corresponding user-configurable routines can be found in the repository. The prestressed bridge, in particular a segment of the latter, has a curved-shaped alignment increasing in height over a length of 70 meter. Alignment-based positioning is an essential part of the structural idealization process here since adaptions would otherwise need coordinate transformations for every newly introduced member. Unbounded tendons are integrated into the web, enforcing a curvature load to balance self-weight. Three piers with a uniform rectangular section support the superstructure. In total, to derive the structural analysis models displayed in Figure 21 four main idealization steps are needed; idealizing the superstructure, creating structural members for the piers, defining their connectivity and creating a load case corresponding to the tendon geometry.

First, alignments representing the girder's webs secondary are derived using the offset to the left and right. The stations related to the bridge are collected and sorted in order to use them as pairs for the derivation of structural members from the superstructure. While looping through this segmentation, corresponding stations are created on the secondary alignments. The girder section at the current curve parameter is split in half and assigned to the applicable web. These sections and the segments' stations are then the inputs for structural members following the secondary alignment. In effect, the ground structure is defined and only connecting members are needed for completion. Either a surface with an aligned coordinate system to define only a transversal stiffness or cross beams that automatically represent this transversal load-bearing direction are used. In both cases, the self-weight needs to be set to zero to avoid double counting. As previously stated, such pure mechanical aspects are best retrofitted in the structural analysis tool but the geometry of the surface or cross beams is generated with the tool.

In the next step structural members are directly derived from the pier geometry. Since the piers use linear placements for positioning, the relation to the main alignment is clear. On the contrary, the corresponding structural members have to be defined in the global coordinate system meaning that the reference to the alignment need to persist on node level. This introduces an inconsistency since points in IFC are either defined on a curve or in cartesian coordinates. Up to now, offsets as distance expressions cannot be regarded here. A workaround transforms the alignment-based positioning to cartesian coordinates which leads to a loss of the reference information. This happens because unambiguous back tracing of offsets is impossible for the inner side of curve-shaped alignments. Further problems occur if the alignment-based positioning of the superstructure is combined with global coordinates in the back-end tool SOFISTIK. The calculation of global coordinates in this work is based on a polyline representation of the alignment. For linear alignments, the points agree with the calculation in SOFISTIK, however, for curve approximations small deviations occur. The reader is invited to review the code for further engagement with the problem. In either case, the approach is used for the piers' structural members.

Connectivity from the pier's top to the corresponding structural nodes on the secondary alignments is then expressed via an eccentric link. This way, the structural member representing the pier is related to three points and unambiguous referencing needs to be controlled using the connection geometry inside the relationship entity. In SOFISTIK, such a connection can be expressed as a node to node constraint then but this approach is not in conformity with the structural analysis view in IFC. A more comprehensive solution should be targeted for an official version of a bridge analysis view.

This thesis proposes another extension of the IFC scheme for transferring the tendon geometry. Structural analysis software often provides an interface for selecting a tendon from a manufacturer database and defining its geometry. Constraints are then checked before the corresponding load case is computed. However, the IFC structural analysis view does not contain a concept for transferring the tendon geometry in this sense. As a work around, the SOFISTIK inputs are directly derived from the building component element in IFC and a load case that contains only a reference to the tendon entity is defined in IFC.

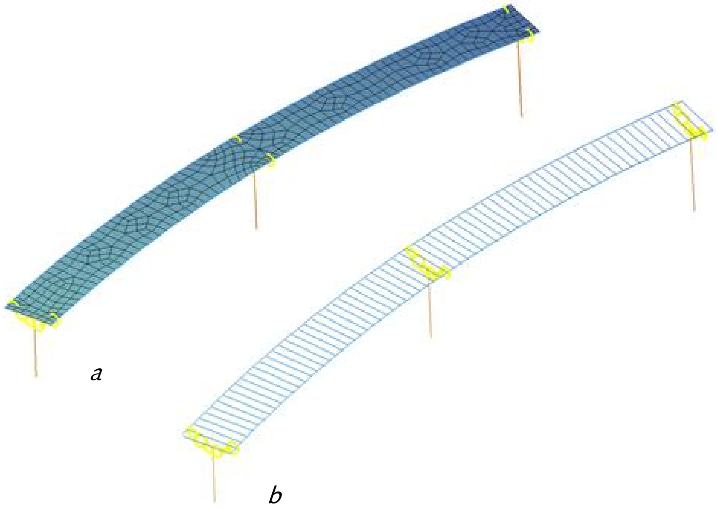

Figure 21: Two different as-generated structural analysis model representing the same double-T-beam bridge; created in the framework and export to SOFISTIK. In (a) a surface is created to connect the two main load-bearing beams. Alternatively, grillage approach (b) consisting of evenly arranged cross beams can be used.

Altogether, two different structural idealizations can be generated as displayed in Figure 21. To demonstrate the effectiveness of both solutions the results of a simple linear analysis are compared. Support conditions are defined and two simple load cases involving self-weight and a variable point load of 1 MN in the middle of the second span on the outer alignment is defined. In this manner, the ability of the models to account section deformations is tested. Comparing the maximal deformation in the global Z direction (at the point of impact 10.3 and 11.0 mm) the values deviate by 5%, which is acceptable due to the varying assumptions. However, the distribution of the bending moment M_y is different (see Appendix C). This leads to the conclusion that the stiffness distribution must be different as well. A possible explanation is that a cross beam contrarily to the surface connects to the main beams at only two points. The surface, despite its orthogonal material, is geometrically constrained to the surrounding elements and thus distributes the load also to the sides. In effect, the cross beam at the point of impact transfers the eccentric point load more equally onto both main beams which leads in total to a smaller maximum moment. The surface model on the other hand exhibits greater moments but also a more realistic solution. This explanation is supported by the fact that concerning only self-weight as a uniform load results in equal bending lines (accompanying figures can be found Appendix C). Both models are valid [28], however, from the comparison it can be seen that structural analysis models are always an approximation of reality and element formulations have a great influence on the calculated load-bearing behavior. Note that according to [28] further refinements of the model are needed which are omitted for the sake of simplicity in this case study.

7.2 Section clipping

To demonstrate damage processing further assessed in section 3.4.3, 4.2 and 6.2.1, a deterioration model of a progressing corrosion process affecting the double-T-beam bridge's superstructure is introduced at the position of the variable load. The aggregated damage variation names crack formation due to expansion of corrosion products as the current phase. This means that not only the reinforcement in this area is affected but also the concrete's stiffness and strength.

As explained in section 3.4.3, this case requires parametrization of material parameters which is done in this example by assigning a new material labeled as damaged to the respective area of the cross-section. For the sake of simplicity, a linear analysis is carried out even though proper material modelling would require nonlinear solving. Instead, the elastic modulus and tensile strength is reduced completely, i.e. a small value is specified to guarantee numeric stability. On the contrary, the shear modulus remains the same since shear forces can be still transmitted due to friction as assessed in chapter 3.4. Applying the decisive load combination (self-weight, variable point load and prestressing) on the bridge the normal stresses displayed in Figure 22 can be obtained. It is clearly visible that the damaged area of the section is not contributing to the flexural capacity. This single damage already affects the load-bearing behavior of the whole structure visible by increased displacement - 7.6% in the load case of the point load - and a slight redistribution of forces showing that the structure can adapted itself to the changes in stiffness. The moment in the field decreases while support moments increase by around 4% (see Appendix C). Interesting to note is that the opposing web is exhibiting a greater moment by around 18% as well. This leads to the conclusion that a combination of small damages can lead to an extensive redistribution of forces and therefore also a different point of failure. However, a nonlinear analysis is then required to determine the ultimate load-bearing capacity.

In this example, a different deterioration type is regarded as well. It is assumed that due to the deterioration of the web the aging process of the unbounded tendon is accelerated leading to a reduction of prestress by 7%. Other scenarios of relaxation are possible as well, e.g. if higher temperatures occur over a extend period of times according to [44]. Since the tendon is unbounded, the deterioration is accounted with a reduction of the corresponding load case by the factor. Ultimately, the balancing effect is decreased and the analysis shows greater moments and displacements in the decisive load combination by around 40% (see Appendix C). Of course, the influence of the tendon on the structural behavior always depends on its design. In this example, relaxation needs to be considered since the durability or serviceability limit state could be affected. Deformation likely results in new crack formations and possibly new spots for degradation.

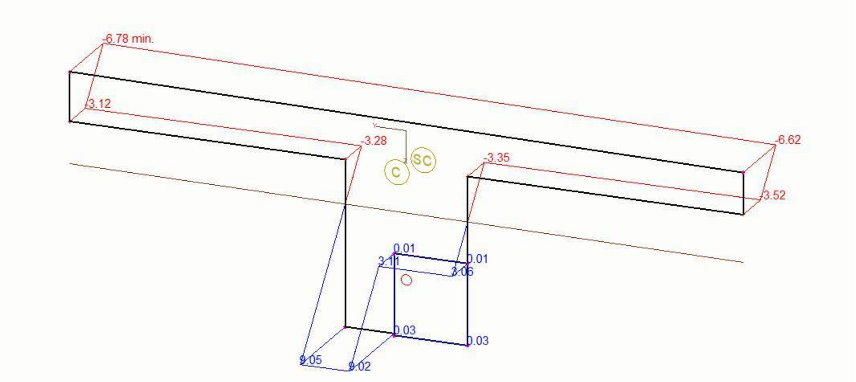

Figure 22: The distribution of normal stresses at the damaged member shows clearly the non-effective part for bending forces of the cross-section. Blue displays tension; red compression in N/mm^2.

7.3 Scherkonde Viaduct

In this section, the processing of data from an image-based inspection of a real structure is shown. Therby, the performance of the developed solution is demonstrated since the subject is a relatively large bridge with a varying girder section that needs a fine discretization. The Scherkonde Viaduct on the high-speed link between Erfurt and Leipzig is further described in [5] and [86] and displayed in Figure 23. The semi-integral railway bridge has been completed in 2011; the data used here originates from an inspection with an unmanned aircraft system in July 2019. The data is then prepared with the framework developed by Morgenthal et al. [5] before it is transferred to the proposed damage information model.

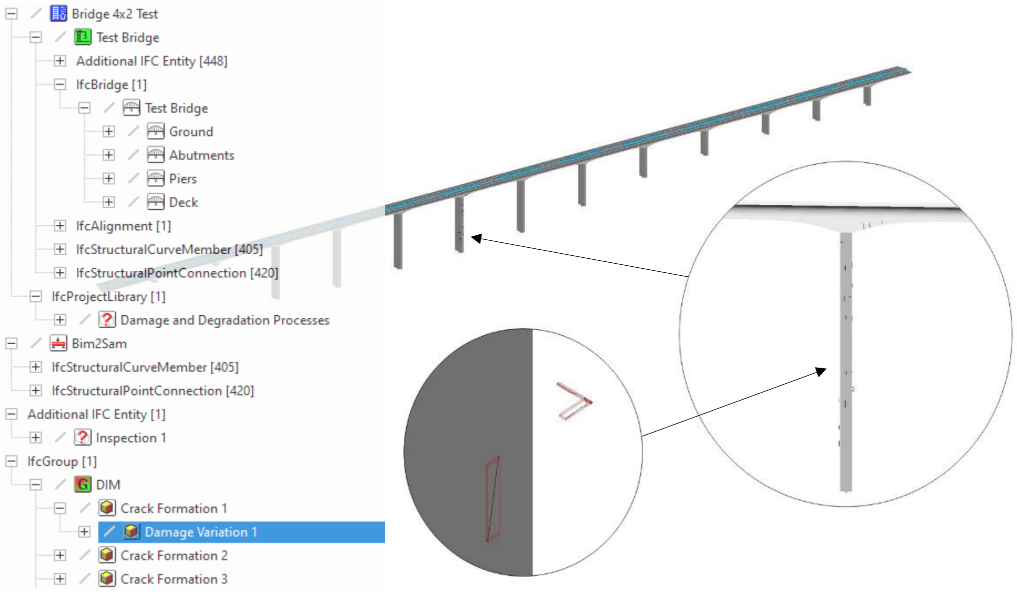

Figure 23: The Scherkonde Viaduct is an integral bridge with a hunched girder visualized with the FZK-VIEWER. Crack patterns from an image-based inspection are mapped on Pier 9. The offset between the projection on the recorded deformed state and implicit design geometry is clearly visible.

As discussed in section 4.3.2, a meaningful damage information model needs to establish a link to the affected building element. Hence, a building information model of the Scherkonde Viaduct is required which is not available in the IFC 4X2 format. For the demonstration purpose, a simplified bridge design model consisting of the superstructure and piers is created with the developed library. Moreover, the structural analysis model is derived. The blue marks in Figure 23 visualize the sequence of structural members needed to represent the varying girder section. Crack patterns from the image-based inspection are then read from an IFC file that stores only the crack geometry and its bounding box. For every pattern a deterioration model with one damage variation is created and referenced to the corresponding pier (see tree view in Figure Figure 23 or Appendix B). The position in global coordinates can be translated to an alignment-based positioning since the straight curve of the bridge allows unambiguous back tracing. The result is displayed in Figure 23 (for the visualization in the FZK-VIEWER [92] the linear placements are translated to global coordinates again). An up-to-now unnamed problem is clearly visible in the zoom lens. Since large structures like the Scherkonde Viaduct experience significant deformation due to temperature differences the recorded pier geometry is displaced. The offset between the implicit geometry of the bridge design model and the projection of crack patterns on the generated surface model cannot be neglected. In other words, digital twins of bridges cannot be static; load-dependent deformation have to be considered. The latter is inherently difficult and solutions using voxel overlaps are currently developed at the Chair of Modeling and Simulation of Structure at Bauhaus-Universität Weimar to allow referencing to building elements nevertheless [93]. Alternatively, the damage geometry can be transformed to fit the design state before it is processed and transferred to the structural analysis model. For future comparison, it is important to store the displaced state in order to persist the relation between the crack geometry and the deformation. Considering the ideas presented in this work, the cause of the crack patterns needs to be determined. Here, the visualization localization in 3D becomes handy since it allows assessment of the overall crack pattern. For example, initial thoughts on the decisive load combination or critical areas are possible. However, the framework is still under development and meaningful parameters for the abstracted damages entities need to be derived before interpretation is enabled. Concerning this case study, cracks are not severe due to the relatively young age of the bridge and no degradation process is recognized up-to-now. But their storage in the damage information model allows localization, comparison and easier interpretation in future.

7.4 Further work

Testing as an integral part of software verification and validation is carried out during development. Further case studies from the last chapter show that the system is valid from the perspective of structural analysis model derivation and damage processing. Unfortunately, the current state and usage of IFC4X2 and damage information does not allow for further validation with real world example data. Other proposals, assessed in section 4.2.2, are facing the same problem. In this chapter, the indented purpose is reviewed instead by comparing it to alternative and possibly more advanced strategies. The constraints on the domain concepts and requirement specifications are revised again in order to retrieve potential limits and extension options of the presented solution.

It is fundamental to ask whether the prerequisites for basic functionality can be fulfilled in most scenarios. Data availability in the right format is the key element here. As demonstrated, structural analysis requires a bridge design model that stores important geometrical properties. In the best case, the model also contains the reinforcement layout. Without this information, only estimations are possible that do not necessarily need a finite element model. This implies that the presented workflow is only meaningful for projects where either a consistent BIM model is available or a subsequent (automated) remodeling of the latter is possible. On the contrary, completeness is usually never ensured, rather, uncertainties are eliminated as far as possible. The more reliable a model is, the more refined methods can be applied. The same dilemma of information availability is recognized for modelling causes of degradations. The models usually require material but also environmental data like temperature or humidity that can be extracted from weather reports in a deemed-to-satisfy approach but more refined methods need higher accuracy in inputs [37]. Loads as causes for mechanical damage can be approximated with the models proposed in standards as well. But tracking traffic or temperature directly or indirectly via monitoring deformations allows a more refined analysis and consequentially reliability statements with a higher degree of certainty. Hence, it is proposed to carry out a feasibility study considering a variety of analysis solutions before choosing the assessment method.

When quantifying the extent and degradation phase of a damage artifact, a high level of inaccuracy must be expected as well. These uncertainties can be reduced by combining visual inspections with bottom-up monitoring approaches and the resulting redundancies are used for assessment [37]. However, the question arises whether the variability in material and structural parameters (like the concrete cover) on the resistance side as well as loads and environmental influences on the impact side are best considered in probabilistic models. For example, instead of describing the reduction of a prestressed tendon area with a linear function a Weibull distribution can include the uncertainties [40]. In section 3.5, such an analysis was shortly introduced as a part of postprocessing and extension of the deterioration models in this direction was named in section 6.2.1. This way, reliability analysis can be enabled on damage and structural element level. However, as proposed in the FIB model code for service life design [50] and demonstrated in [94], the extent of a degradation can be specified on system level independent of modeling damage artifacts and structural analysis as well (see [95] for an exemplary implementation for the Scherkonde Pier in Python). Here, predictions concerning the overall structural condition valuable for life-cycle management can be already made similarly to the safety formats commonly used in structural engineering. In particular, a durability limit state is determined comparing for example the mean carbonatization depth to the concrete cover [96]. As shown by Stewart [97], updating of such predictions with information from visual inspections is possible. In this approach, heterogeneity in deterioration extents is considered by applying a random field theory and hence it is decoupled from single damage artifacts. Additionally, observed deterioration points lead to element-specific updates. In [40] degradation processes specifically describe the deterioration of a structural region or element. In total, it can be seen that information availability can lead to more refined models also here. If the reliability or failure of a structure shall be revised completely nonlinear structural analysis and the implementation of the presented approach to degradation modelling are essential [40], [44]. The probability-based assessment is, for example, enabled with the software tool SARA [98] but also SOFISTIK [26] allows for formulating custom limit state functions. This leads to the conclusion that the approach of this work will profit from the introduction of probabilistic models. As the suitable method is chosen by the structural engineer, this task is part of postprocessing meaning that only the necessary inputs of degradation models must be supplied by the BIM (material and structural parameters) and the DIM (extent and progressing) for the beginning. However, in accordance to the methodology of this work it is recommended to carry out a domain analysis before implementation.

Monitoring data can present further information for model updating but also for statistical evaluation [37]. If sensor data is used to calibrate the model and evaluate the simulation results additional raw data needs to be prepared and referenced in the DIM. The works of Theiler and Smarsly [99] on monitoring systems and Taraben et al. [58] on monitoring outputs discuss solutions within the IFC format. Extension in this direction could lead to a more generalized framework and further quantitative values describing damages. As already stated in section 4.2.2, modularization is a key element when introducing new concepts and it is expected that the development will profit from flexibility of the IFC format.

On the contrary, image-based inspections are identified as the main source of damage information so far. In the deterioration model, the recorded data is abstracted with a discrete damage geometry like the polyline crack representation, which is not further processed, and a bounding box that is used for interpretation. Critically reflected, the presented clipping procedure is only the first step towards automated damage processing since it overestimates the damage to deal with the uncertainties. Concerning the modelling of degradation processes, the surface exposed to environmental influences is interesting to evaluate the progression. Then, quantitative parameters describing the extent can be derived. The pictures used for the generation of the projection can contain further valuable details like traces of rust that are only identifiable by humans so far. As already stated in chapter 4, this information cannot be directly used; it needs standardized measurement and interpretation methods to obtain meaningful damage information models from it. If these prerequisites are fulfilled, more refined processing methods involving fraction mechanics or artificial intelligence can be developed.

The clipping procedure as an approach to structural analysis idealization of deteriorations has to be evaluated further. Since wireframe and surface models are chosen to represent the mechanical behavior, damage processing is restricted to them. Especially, for beams this limits concepts to the cross-sectional level. This approach is in accordance with common bridge design and simplifies analysis; the main reason why it is chosen in this work. Due to the characteristic of beam elements, section deformation is not considered in such a model as previously mentioned in chapter 3. Deterioration, e.g. of the web of a hollow girder section, can affect the integrity significantly and section deformation have to be considered then (see validation in Appendix D). In the current approach, the structural engineer has to be aware of these drawbacks and apply refinements when necessary. The latter could lead to overly complex models implying the need for an alternative approach. Volumetric representations allow with remeshing a direct damage transfer without the need to consider mechanical aspects of the idealized system, like section deformations. As evaluated in chapter 5, this method presents a more direct way to transfer the geometry to structural analysis. With the advancement made in FEM, extensive studies of the load-bearing behavior based on a three-dimensional stress state are enabled. Further comparisons have to proof which approach facilitates the automated derivation and modelling of damage artifacts in structural analysis models.

When recapitulating the purpose of automation, the goal is to achieve an efficient way to process damage information from inspections in structural analysis models. The transfer to various analysis tools is enabled in this work by using the interoperability format IFC. Even though its use is increasing in the domain, the question how structural engineers can interact with the transfer process is left open. Up-to-date, the user has to engage with the software routines and customize them on this level which requires programming skills and time. As introduced in chapter 5, an interface that allows to interact with the generation process by supplying a set of easy-to-understand operations can be solution [79], [80]. Further customization possibilities of the IFC export from BIM-centered tools can facilitate such transfer processes as demonstrated in [74]. At best, software vendors, institutions like BS, practitioners and scientist will work together on a collaborative approach to damage processing and find a practicable solution.

8 Concluding Remarks

As stated in the introduction, this work is focused on the lack of interoperability between building information models and structural analysis software in bridge life-cycle engineering. An integral view on life-cycle management, the ability to predict the service life and emerging digital methods establish a basis for the development of a damage information model. Such a model prepares data for subsequent analysis tasks and therefore enables an efficient way to process damage information from inspections in structural analysis models. Before implementation, the information sources and requirements of the domains are analyzed. In particular, the prerequisite of a bridge design model is identified meaning that structural information like material, cross-section geometries positioned along the alignment has to be made available in an interoperable data format. Alternatively, the structural analysis model created for design can be reused. In the same manner, representations of damage artifacts are evaluated from the perspective of damage modeling in structural analysis. For this, the affected structural parameters like dimensions, stiffness or strength need to be determined. Thinking outside the box, information about the deterioration is interesting for other disciplines as well and a cause-effect relationship is seen as the central entity in this work. The developed, abstract representation therefore specifies the degradation process and its progression and gives information about the geometrical extent of the damage. However, quantifying the latter is difficult and solutions are discussed in chapter 7.4. In total, the information structure is defined and a suitable data model needs to be found. IFC as the emerging interoperability format in the domains of architecture, engineering and construction is chosen since it provides suitable concepts for architectural and structural analysis representations as well as flexible extension mechanisms. Further, this format has the advantage that it will be used for information handover in the future which allows for the reuse of the design model for maintenance. Furthermore, structural and material parameters that are reviewed during construction can lead to an update of the latter. The IFC 4X2 bridge extension presents already concepts for bridge design model and a suitable damage information model and structural analysis representations for superstructure, pier and damage elements are additionally proposed in this work. Since discrepancies exist between the representation of bridge elements in the design model and the digital twin, i.e. recorded data, alignment-based positioning is chosen as the common element to connect information from both sources. This way, the position of deteriorations and their extent is combined with the architectural model setting the basis for the derivation of a structural analysis model of the damaged state. Concerning the automation of this process, the need to interact with the transfer processes is identified. In particular, the user should be able to interpret the information and decide flexibly how the resulting model represents the mechanical system. Different approaches to automated model derivation are analyzed and an adapted procedure based on semantic enrichment of IFC data is proposed. The idea is to consider always a subset of operations on a specific stage, i.e. model, that can be summarized in an interpretation task. A prototype implements this concept and is validated carrying out a case study on an exemplary double-T-beam bridge. The possibility to create different idealizations of the mechanical systems is demonstrated and the effects of a simple deterioration model are shown. In the process, damage information that is mapped to the architectural representation is interpreted in the structural analysis model on cross-sectional level with a clipped area specifying a deteriorating material and thereby quantifying the damage extent. However, during validation several loose ends are identified and further extension and comparison is proposed. When analyzing existing structures, material and structural properties, load models and load-bearing behavior can be experimentally determined. Values from design codes should only be used if such investigations are unfeasible. Dealing with uncertainties in this data, probabilistic methods are enabling statements on the structural reliability nevertheless. It is therefore a key element in future building information models to combine information from design, which marginally deviates from the as-built state like the dimensions, with recorded data from construction, image-based inspections or structural health monitoring systems. The distributions of these measured values are important inputs for degradation models and reliability analysis. Extension of the damage information model is therefore proposed in this direction. The serviceability and limit state functions are essential concepts in structural design; collecting inspection and monitoring data allows to set up a durability limit state function and predict the condition of the current state. It is important to notice that such a function is not necessarily coupled to a mechanical analysis. Durability is already affected with the depassivation of concrete leading to corroding reinforcement as validated. Hence, solely structural properties are compared, like the concrete cover and the depassivation depth. Therefore, it is interesting to assess if probabilistic degradation models can be calibrated with the derived properties of damage information model items. In conjunction with structural analysis, reliability statements are enabled then. Thereby, mainly the postprocessing method need to be refined due to the need of statistical sampling during simulation. The tool-based derivation of structural analysis models remains meaningful here. In total, a general workflow as targeted by the developed prototype must be independent of the refinement level of analysis. It only prepares information efficiently and results - together with the chosen assessment method- in a knowledge gain for structural engineers.

9 Bibliography

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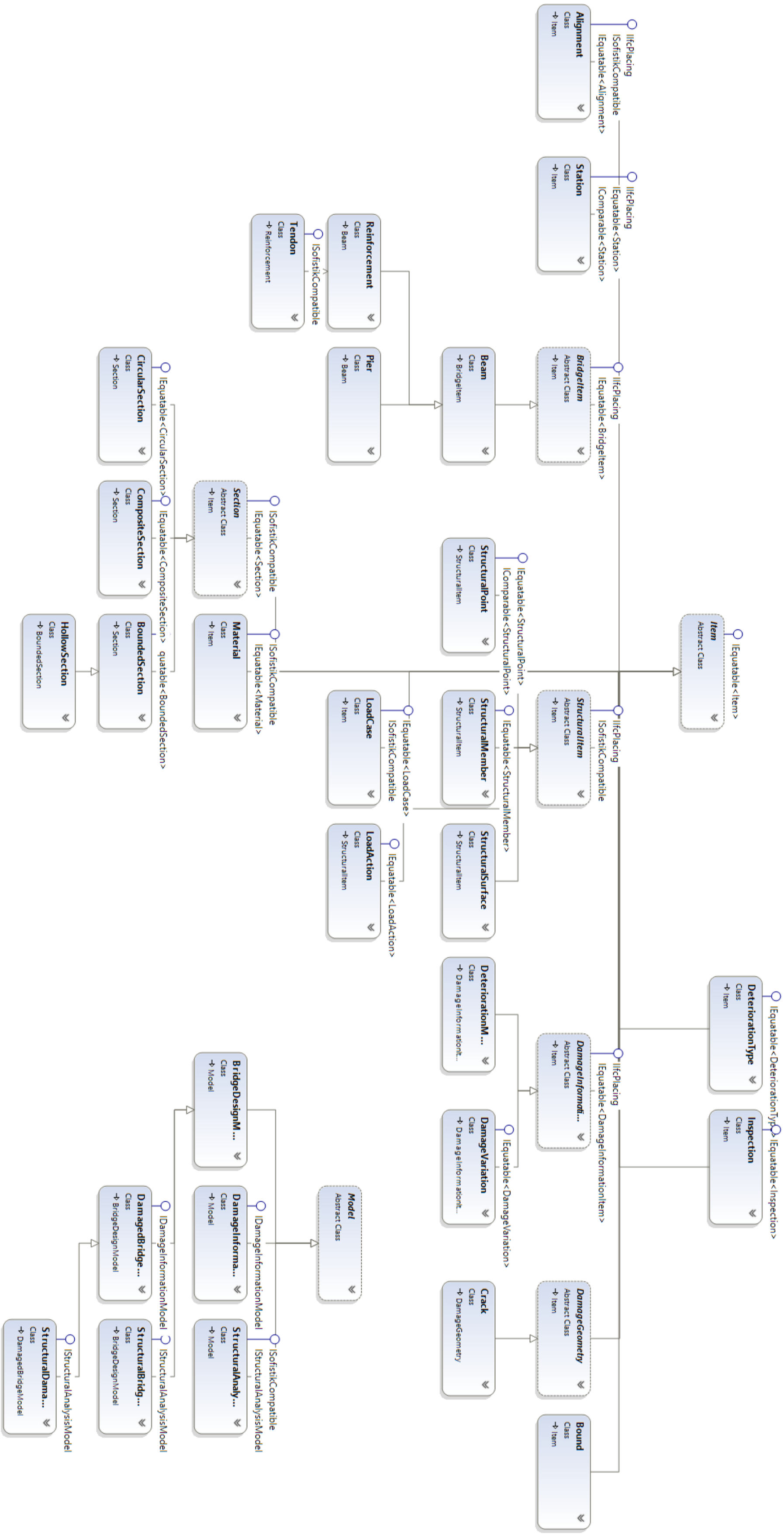
Appendix

Appendix A



Appendix B

The example double-T-beam bridge is explained using fractions of the generated IFC file.

Bridge Design Model

Alignment-based positioning

```
#205=IFCALIGNMENT('1HfXQOnJnFaQjWGNYdA0_M',#197,'B',$,$,#24,$,#206,.NOTDEFINED
.);
#206=IFCOFFSETCURVEBYDISTANCES(#30, (#207),$);
#207=IFCDISTANCEEXPRESSION(0.,-2750.,0.,$,$);
#208=IFCRELPOSITIONS('2mK0GglCzB0eyhJVDuYIER',#197,$,$,#205, (#219,#223,#231,#2
39,#247,#342,#366,#390,#414));

#219=IFCREFERENT('2HhA7RJn96QODykgeHk_07',#197,'B20',$,$,#218,$,.STATION.,$);
#220=IFCRELPOSITIONS('1EI3SWv4b7Kf4U9sICthXi',#197,$,$,#219, (#291));
#221=IFCDISTANCEEXPRESSION(90000.,$,$,$,.F.);
#222=IFCLINEARPLACEMENT(#24,#206,#221,$,$);
```

Listing 5: Positioning elements are set first. Alignments use curves or linear segments and referents distance expressions inside linear placements. Corresponding relationships highlight the reference to the positioned elements.

Superstructure

```
#173=IFCSECTIONEDSOLIDHORIZONTAL(#30, (#140,#140,#158,#158,#140,#140,#158,#158,
#140,#140), (#47,#51,#55,#59,#63,#67,#71,#75,#79,#83),.F.);
#174=IFCBEAM('22pVO0lvfEpOMatUBjw92U',#2,'Test
Girder',$,$,#170,#175,$,.GIRDER_SEGMENT.);
#175=IFCPRODUCTDEFINITIONSHAPE($,$, (#176));
#176=IFCSHAPEREPRESENTATION(#19,'Body','AdvancedSweptSolid', (#173));
#177=IFCMATERIALPROFILESETUSAGE(#142,8,$);
#178=IFCRELASSOCIATESMATERIAL('20WtK8Wlf9eAMlaFTlLvwH',#2,$,$, (#49),#177);
```

Listing 6: The main girder is represented by a sectioned solid which uses distance expressions to position cross-sections along the alignment curve. Material profile sets are assigned to the station referents to allow their tracking.

Structural Analysis Model

Structural Point

```
#291=IFCSTRUCTURALPOINTCONNECTION('25BfEx_cj13xyGE7dsTdfJ',#197,'3',$,$,#24,#2
92,$,$);
#292=IFCPRODUCTDEFINITIONSHAPE($,$, (#293));
#293=IFCTOPOLOGYREPRESENTATION($,$,'Vertex', (#289));
#294=IFCVERTEXPOINT(#295);
#295=IFCPOINTONCURVE(#206,0.617983134665562);
```

Listing 7: Structural elements use topology items for representation. Here, a vertex points wraps a point positioned on the alignment curve using a computed parameter value. Note that the same placement of the site is used for positioning and structural elements.

Structural Member

```
#330=IFCSTRUCTURALCURVEMEMBER('05ULIPoNjA18spx8pcTwiq',#197,'1',$,$,#24,#331,.
RIGID_JOINED_MEMBER.,#335);
#331=IFCPRODUCTDEFINITIONSHAPE($,$,(#332));
#332=IFCTOPOLOGYREPRESENTATION($,$,'Edge',(#333));
#333=IFCORIENTEDEDGE(*,*,#334,.T.);
#334=IFCEDGECURVE(#279,#284,#329,.F.);
#335=IFCDIRECTION((0.,0.,1.));
#336=IFCRELASSIGNSTOPRODUCT('2uistW_7z91RnUCy2GX$f8',#197,$,$,(#330),$,#137);
#337=IFCRELCONNECTSSTRUCTURALMEMBER('1oYRxzbKj5IRAYjy9Egclb',#197,$,$,#330,#28
1,$,$,$,$);
#338=IFCRELCONNECTSSTRUCTURALMEMBER('2tyI_w$2b6O9ELOBhmCY$H',#197,$,$,#330,#28
6,$,$,$,$);
#339=IFCMATERIALPROFILESETUSAGE(#265,8,$);
#340=IFCRELASSOCIATESMATERIAL('16$_$R5rPDmf7opOXXCrBh',#197,$,$,(#330),#339);
```

Listing 8: a structural member uses a trimmed segment of its alignment as a representation. Further information like the connection to the end points and section is given by relations.

Damage Information Model

```
#634=IFCGROUP('05VC4ijdjBqBi_zLUke_FY',#626,'DIM','Damage Information
Model',$);
#635=IFCRELASSIGNSTOGROUP('0jxn3qdXr2DfykYa0j_ViJ',#626,$,$,(#645,#746,#757),$
,#634);
#636=IFCPROJECTLIBRARY('3d$gMY71nCsudvLL5vdEyO',#626,'Damage and Degradation
Processes',$,$,$,$,$,$);
#637=IFCRELDECLARES('3M$6dQu2jFNQKy$AuSAddg',#626,$,$,#636,(#638,#643));
#638=IFCPROPERTYSETTEMPLATE('3yX_QkpmT2ZxOO4FnKDmNU',#626,'Degradation Process
Information',$,.PSET_TYPEDRIVENOVERRIDE.,$,(#639,#641));
#639=IFCSIMPLEPROPERTYTEMPLATE('23qoW8MerF8g4vOSrGLFiG',#626,'Phase','Phase of
a typical degradation
process',.P_ENUMERATEDVALUE.,$,$,#640,$,$,$,.READWRITE.);
#640=IFCPROPERTYENUMERATION('PEnum_Phase',(IFCLABEL('Depassivation'),IFCLABEL(
'Corrosion'),IFCLABEL('Crack formation'),IFCLABEL('Spalling'),IFCLABEL('Loss of
reinforcement')),$);
#641=IFCSIMPLEPROPERTYTEMPLATE('15zIL5ryvCJ9j0p4e6ePTR',#626,'Mean Penetration
Depth','Measured or estimated depth of
penetration',.P_SINGLEVALUE.,$,$,$,$,$,$,.READWRITE.);
#642=IFCRELDEFINESBYTEMPLATE('1$ObnWu5T4gRqP8kKCY5FQ',#626,$,$,(#753,#764),#63
8);
#643=IFCBUILDINGELEMENTPROXYTYPE('1QUVlYstfDwuHCyUnCc7DH',#626,'Carbonatizatio
n',$,$,$,$,$,'Chemical',.USERDEFINED.);
```

Listing 9: a group represents the damage information model. Further information and templates are assigned to a project library like deterioration types and degradation phases. Later on damage variations implement the template.

Deterioration Model

```
#623=IFCDISTANCEEXPRESSION(32000.,5500.,$,$,.F.);
#624=IFCLINEARPLACEMENT(#24,#29,#623,$,$);
#625=IFCREFERENT('14xGA026T91Qno7gZMNojV',#626,'032',$,$,#624,$,.STATION.,$);
#630=IFCRELPOSITIONS('0u_ACq$lj4jfDq6JIopWkS',#626,$,$,#625,(#645));
#644=IFCRELDEFINESBYTYPE('3lvaYLuLvDXggLDGH5op7c',#626,$,$,(#645),#643);
#645=IFCBUILDINGELEMENTPROXY('34fG_Ql6LF6eJImfOOYFxQ',#626,'Damage at T-
Beam',$,'Deterioration Model',#624,$,$,.USERDEFINED.);
#646=IFCRELCONTAINEDINSPATIALSTRUCTURE('101JHeN6f6ixYhsq4We_ZB',#626,$,$,(#645
),#129);
#647=IFCRELAGGREGATES('0dnws2bJf4I9qDd3vQ2ry0',#626,$,$,#645,(#746,#757));
```

Listing 10: the deterioration model units its damage variation in one entity. It is positioned by a station and is defined by at least one type.

Damage Variation

```
#13078=IFCPROPERTYSET('3h8rP9PCz7aP0Ye_kHzjhV',#12243,'Degradation Process
Information',$,(#13079,#13080));
#13079=IFCPROPERTYENUMERATEDVALUE('Phase',$,(IFCLABEL('Depassivation')),#12476
);
#13080=IFCPROPERTYSINGLEVALUE('Mean Penetration
Depth',$,IFCLENGTHMEASURE(0.3),$);
#13081=IFCRELDEFINESBYPROPERTIES('05XzBhYZX9XecEMoBFOMRi',#12243,$,$,(#13054),
#13078);
#13082=IFCBUILDINGELEMENTPROXY('18wgYkAMT2qAJS7yFZH1qu',#12243,'Damage
Variation 1',$,'Damage Variation',#13083,#13086,$,.USERDEFINED.);
#13083=IFCLOCALPLACEMENT(#12331,#13084);
#13084=IFCAXIS2PLACEMENT3D(#13085,$,$);
#13085=IFCCARTESIANPOINT((0.,0.,0.));
#13086=IFCPRODUCTDEFINITIONSHAPE($,$,(#13087,#13088));
#13087=IFCSHAPEREPRESENTATION(#19,'Box','BoundingBox',(#12642));
#13088=IFCSHAPEREPRESENTATION(#19,'Body','Curve3D',(#13090));
#13089=IFCRELINTERFERESELEMENTS('03lbuvcenBXPsfUSlmVaST',#12243,$,$,#13082,#46
62,#13098,$,.T.);
#13090=IFCPOLYLINE((#13091,#13092,#13093,#13094,#13095));
#13091=IFCCARTESIANPOINT((9.767894057802096,0.,229.19080840389938));
#13092=IFCCARTESIANPOINT((34.996393353651456,56.25975278906026,189.00274195360
112));
#13093=IFCCARTESIANPOINT((8.359957156585551,43.857129709934384,109.57043530208
921));
#13094=IFCCARTESIANPOINT((12.158928669009583,69.26410897547441,76.192272627906
73));
#13095=IFCCARTESIANPOINT((0.,77.34899379497051,0.));
#13096=IFCVERTEXPOINT(#13091);
#13097=IFCVERTEXPOINT(#13095);
#13098=IFCCONNECTIONCURVEGEOMETRY(#13099,$);
#13099=IFCEDGECURVE(#13096,#13097,#13090,.T.);
```

Listing 11: A damage variation has a bounding box representation (here: IfcBoundingBox but also IfcFacetedBrep for complex shapes is possible) and is placed relative to the deterioration model. Further information like the inference geometry or properties are assigned via relations.

Damage Analysis Model

Damaged Section

```
#135=IFCMATERIAL('C40/50',$,'Concrete');
#599=IFCMATERIAL('Damaged 1',$,'Concrete');
#600=IFCCOMPOSITEPROFILEDEF(.CURVE.,$,(#615,#624),$);
#601=IFCMATERIALPROFILESET($,$,(#616,#625),#600);
#602=IFCPOLYLINE((#603,#604,#605,#606,#607,#608,#609,#610,#611,#612,#613,#614)
);
```

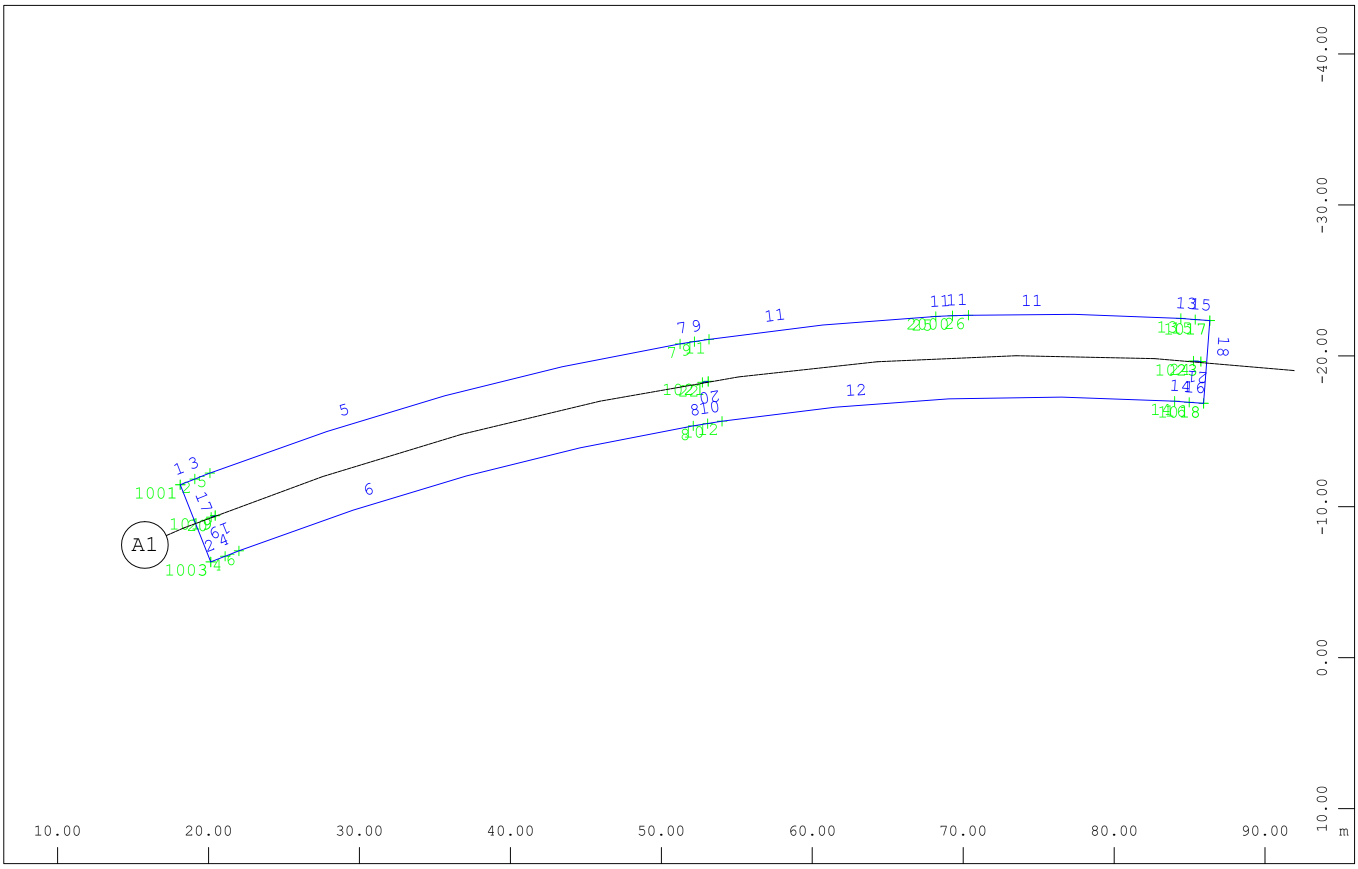
```
#615=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,$,#602);
#616=IFCMATERIALPROFILE($,$,#135,#615,$,$);
#618=IFCPOLYLINE((#619,#620,#621,#622,#623));
#619=IFCCARTESIANPOINT((2750.,50.));
#620=IFCCARTESIANPOINT((2500.,43.));
#621=IFCCARTESIANPOINT((2500.,-50.));
#622=IFCCARTESIANPOINT((2750.,-50.));
#623=IFCCARTESIANPOINT((2750.,50.));
#624=IFCARBITRARYCLOSEDPROFILEDEF(.AREA.,$,#618);
#625=IFCMATERIALPROFILE($,$,#599,#624,$,$);
#626=IFCMATERIALPROFILESET($,$,(#625),$);
```

Listing 12: A damaged section is displayed. It is represented by a composite profile that consist of to polygonal defined sections with differently assigned materials.

Appendix C

double-T-test-grillage.dat
double-T-test-surface.dat
double-T-test-surface-damaged.dat

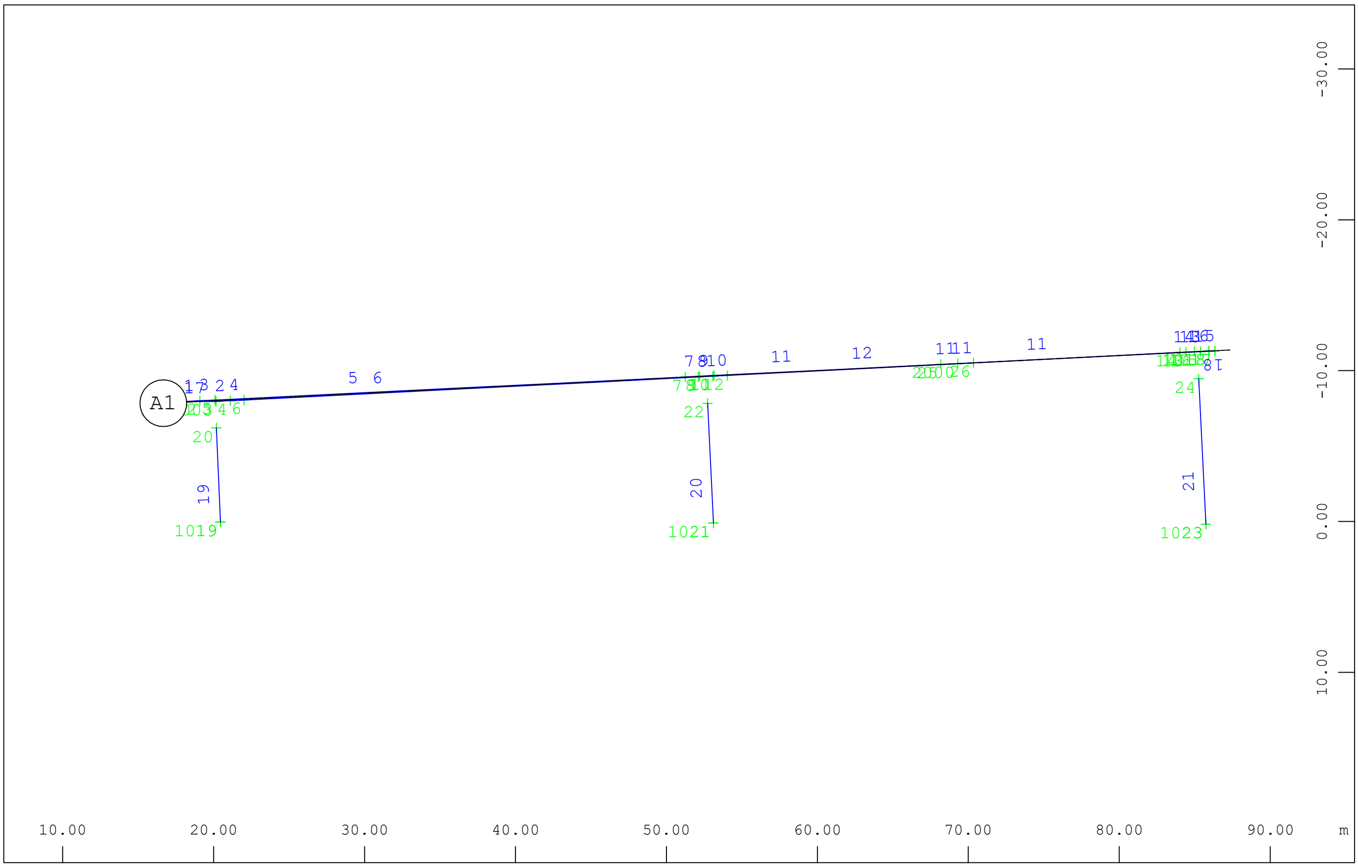
double-t-test-grillage.gra
double-t-test-surface.gra
double-t-test-surface-damaged.gra



Structural points and lines

M 1 : 500

Z X
Y

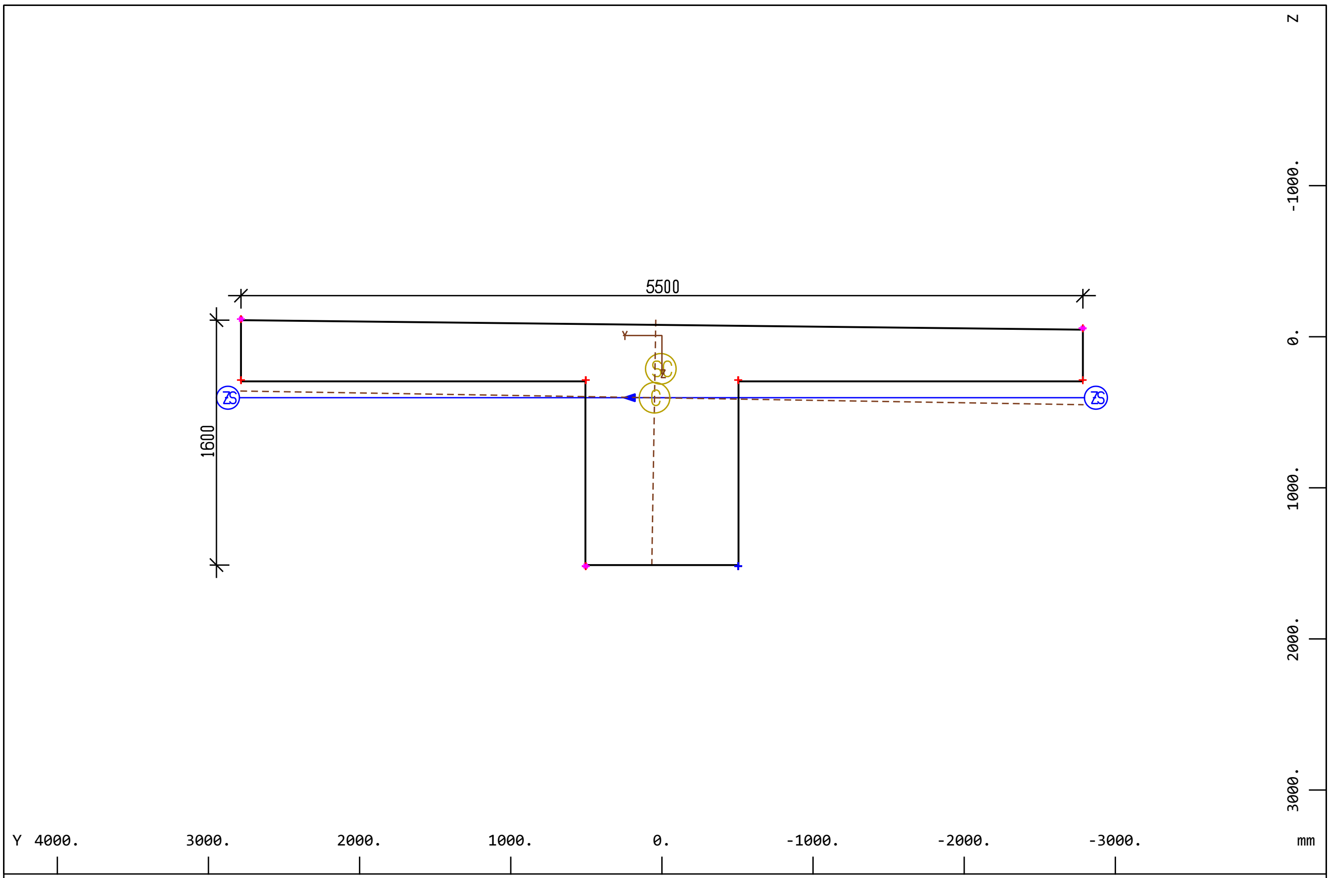


Structural points and lines

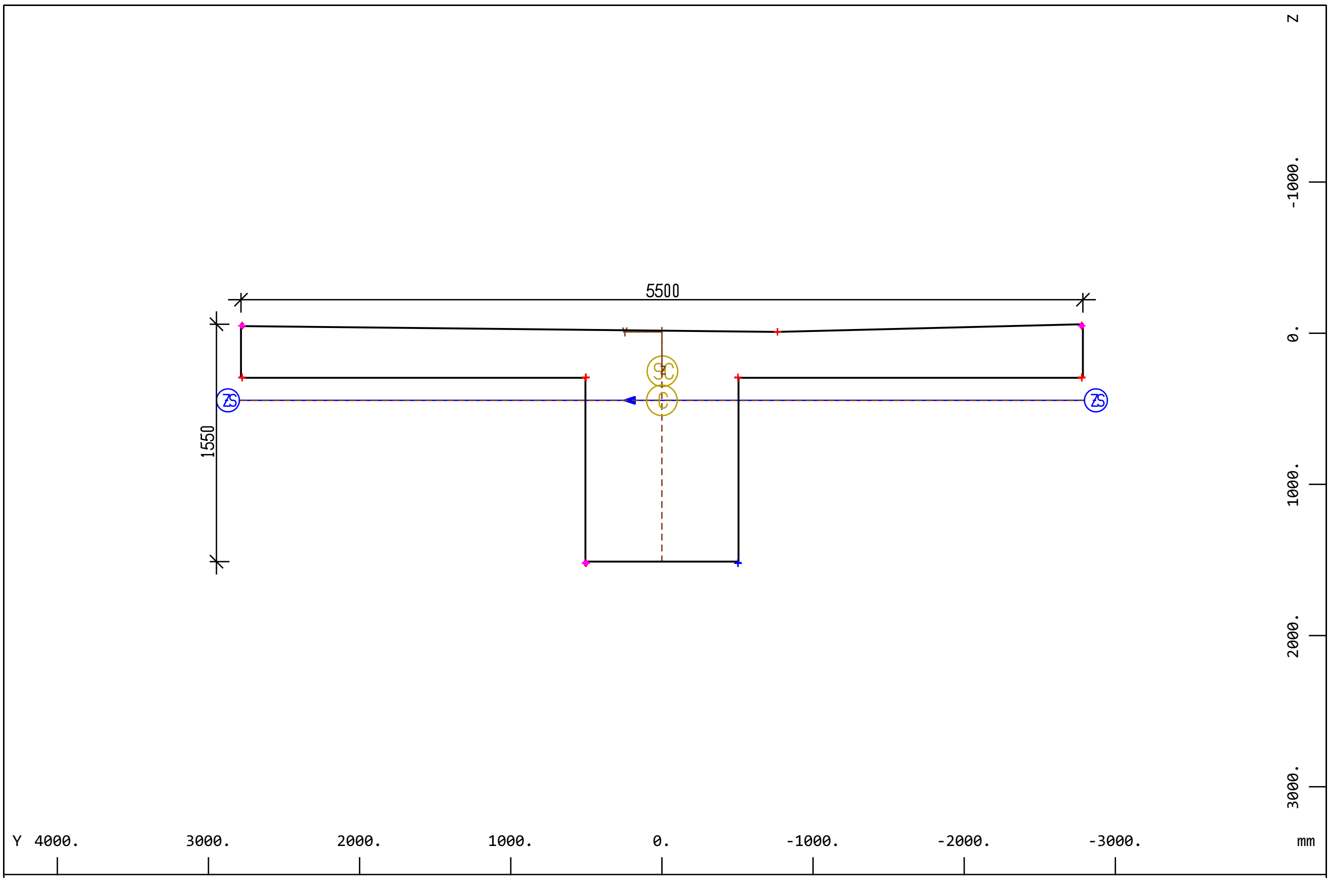
M 1 : 500

Y X
Z

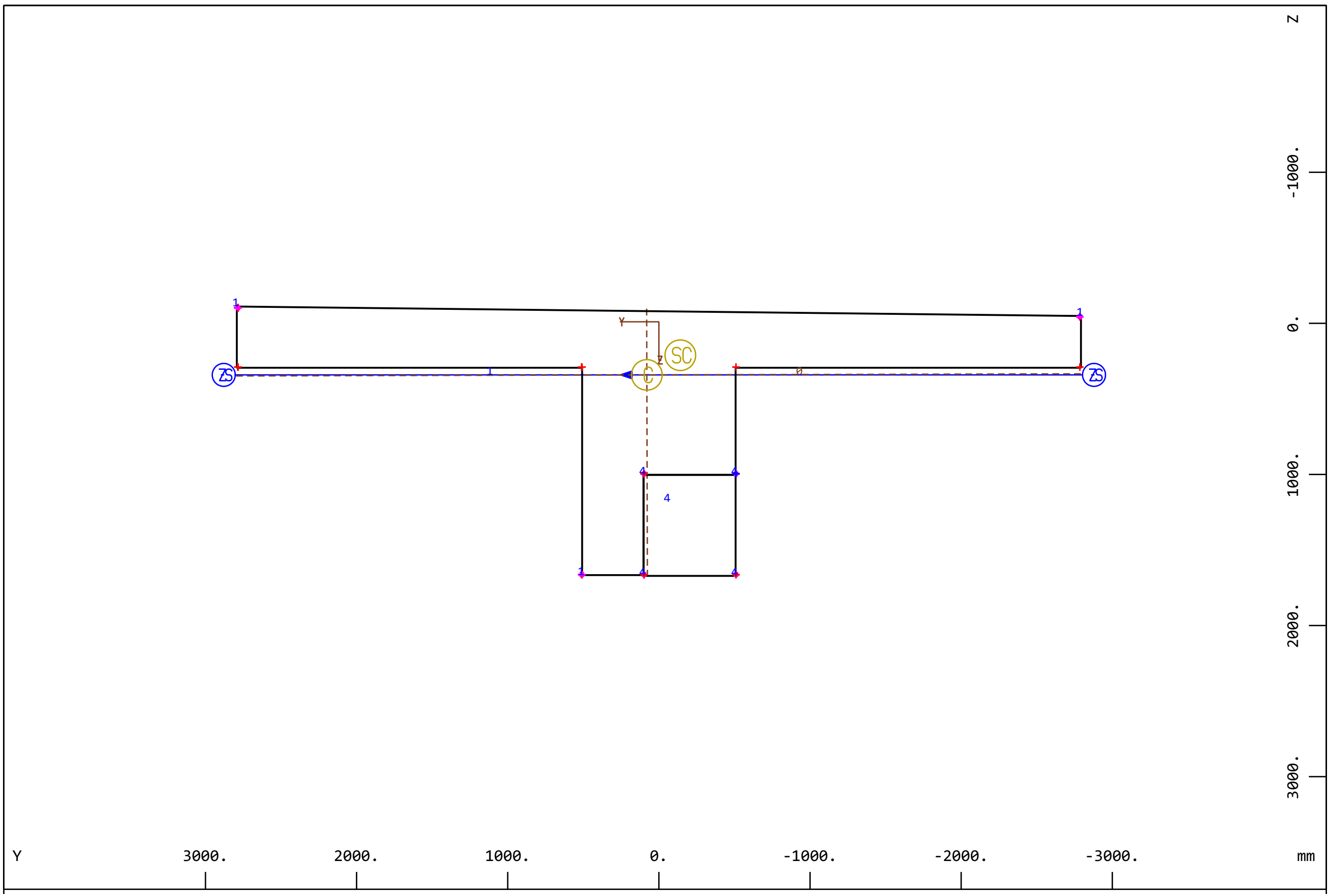
Structural Points and Lines from SIDI



Y Z Querschnittsübersicht Querschnitt Nr. 5 Querschnitt Nr. 5 M 1 : 50

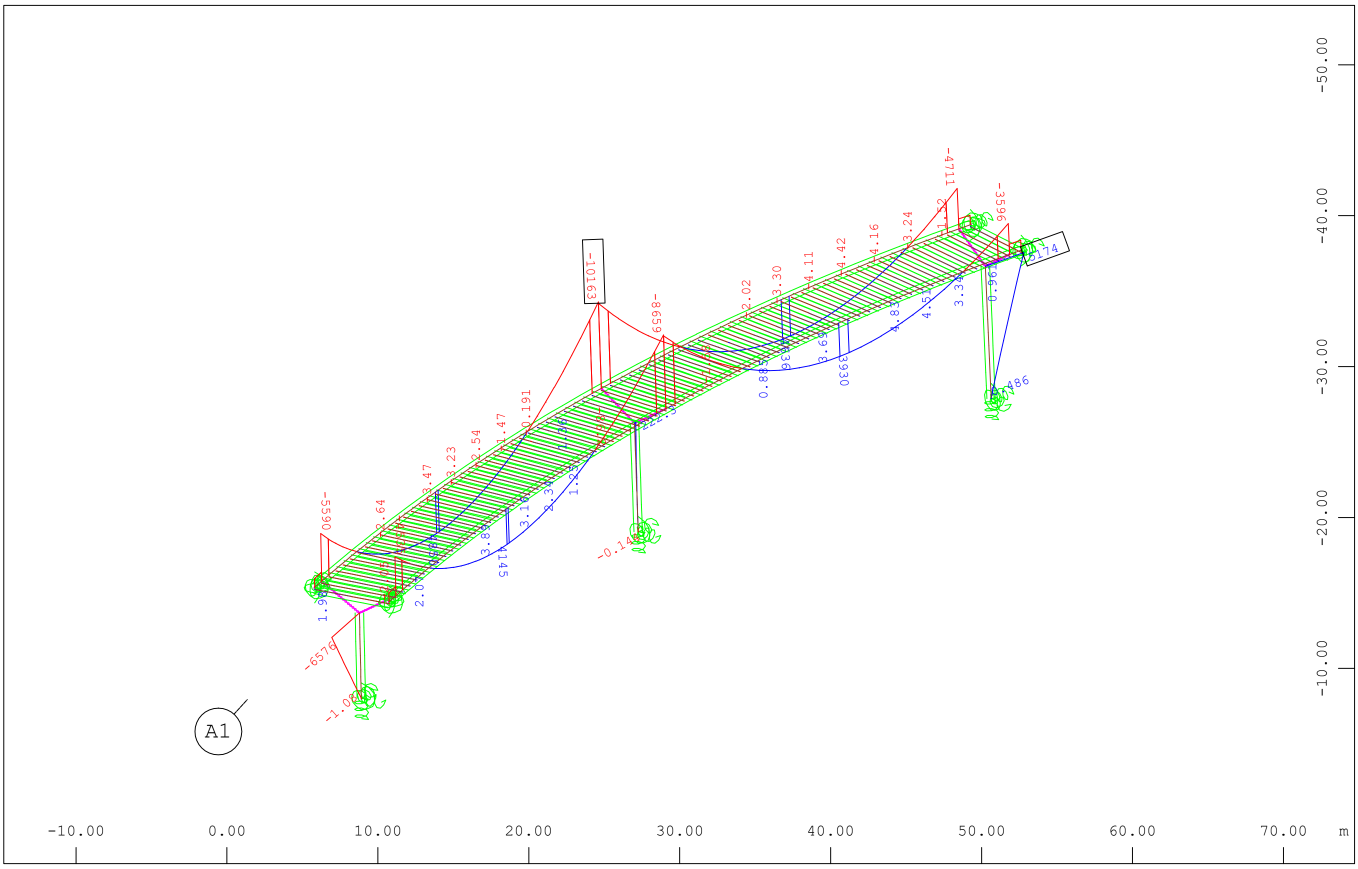


Y Z Querschnittsübersicht Querschnitt Nr. 6 Querschnitt Nr. 6 M 1 : 50



Alle Querschnittselemente Material Querschnitt Nr. 14 Querschnitt Nr. 14

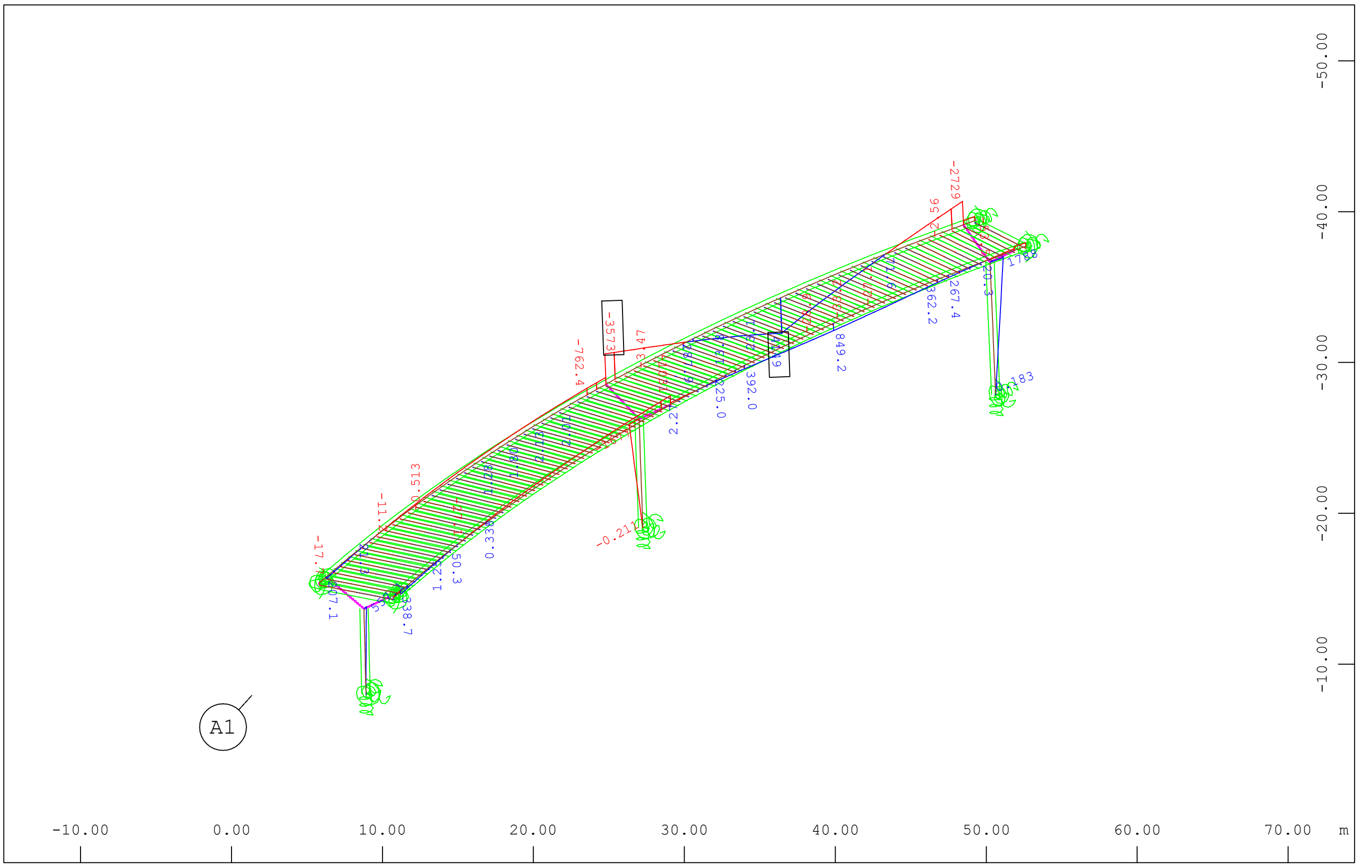
M 1 : 50



X
Y
Z

Beam Elements , Bending moment My (Maximum values cubic interpolated), Loadcase 1 dead load , 1 cm 3D = 8008. kNm (Min=-10163.) (Max=5174.)

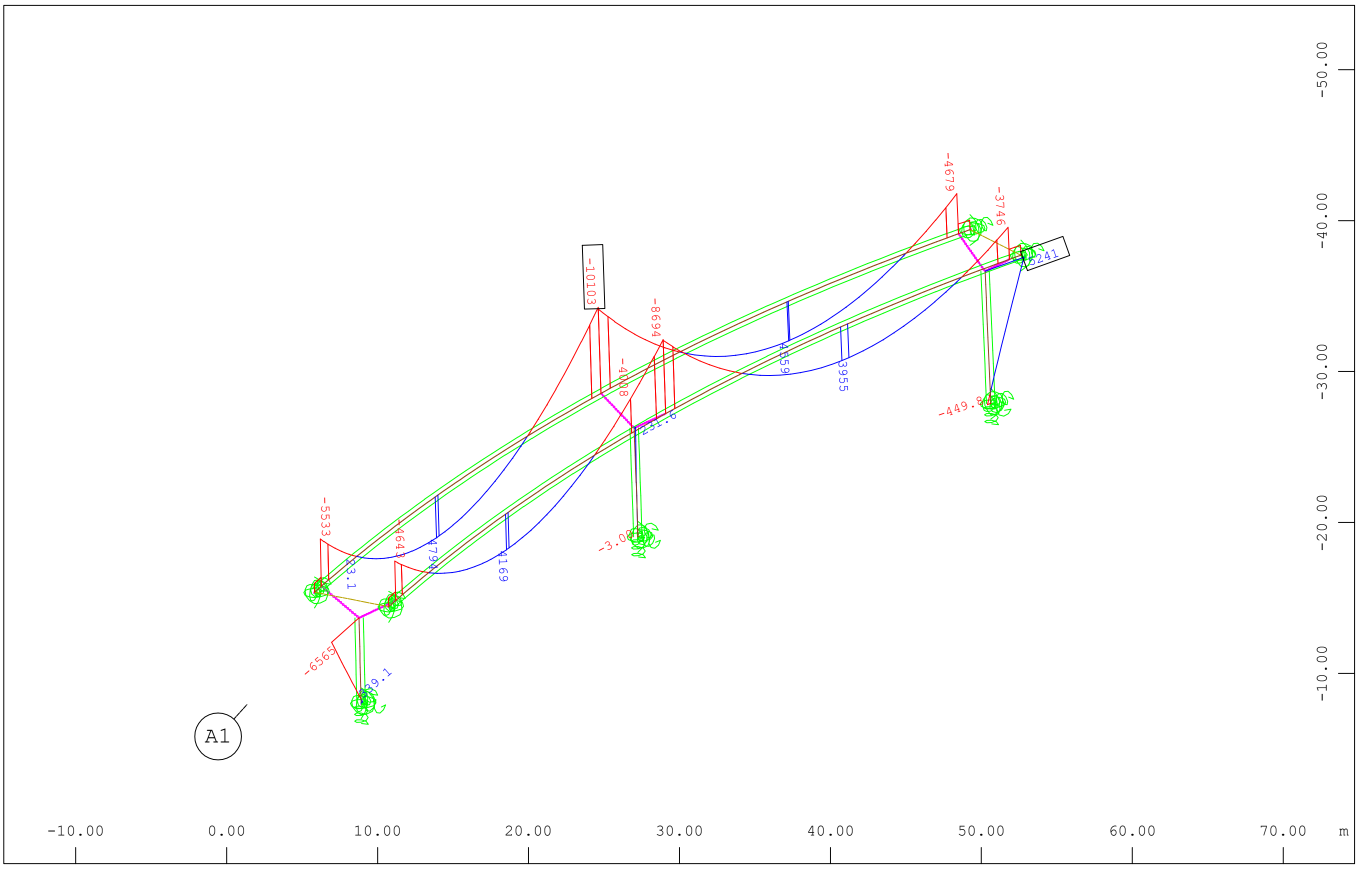
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Beam Elements , Bending moment My, Loadcase 2 test case , 1 cm 3D = 8008. kNm (Min=-3573.) (Max=4149.)

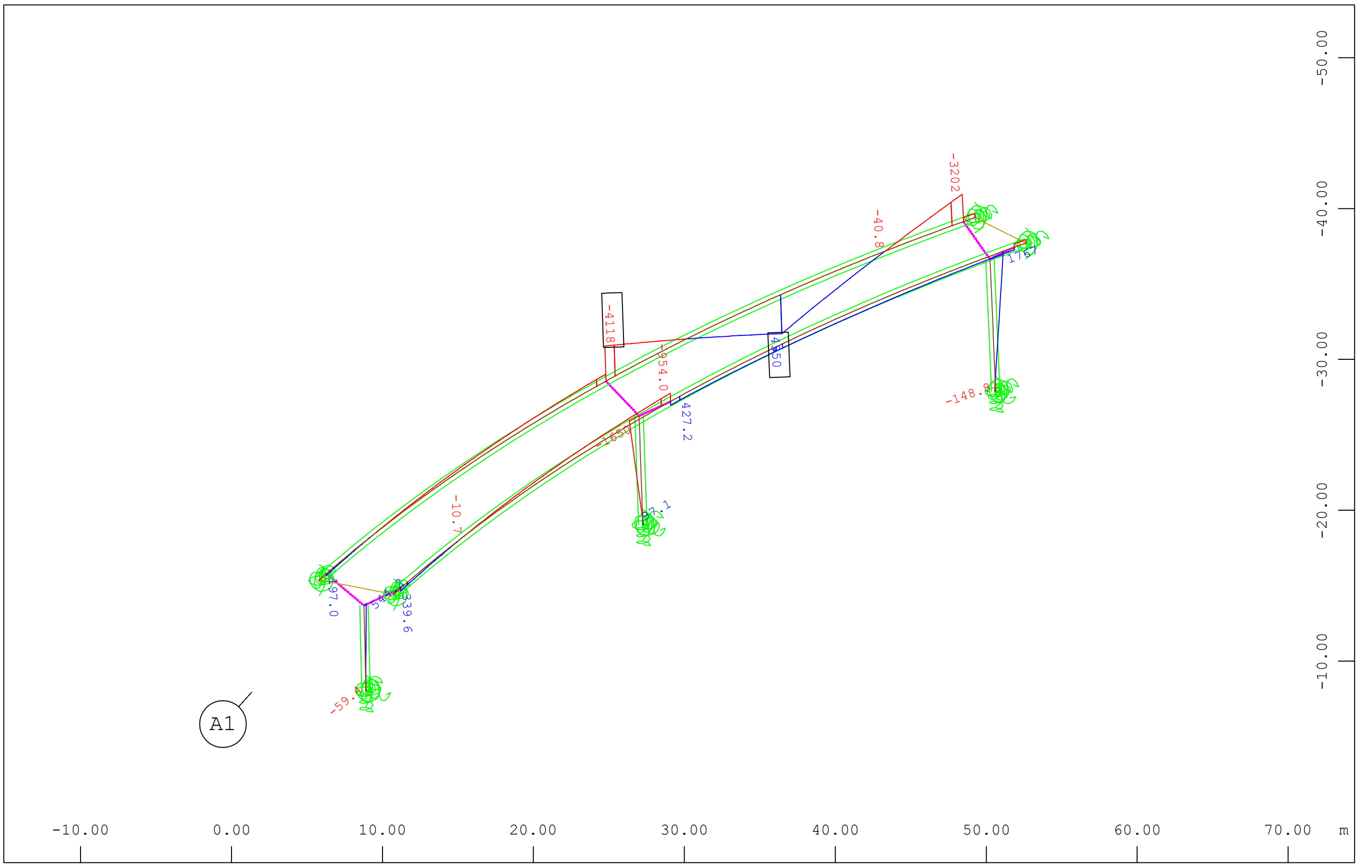
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Beam Elements , Bending moment My, Loadcase 1 dead load , 1 cm 3D = 8008. kNm
(Min=-10103.) (Max=5241.)

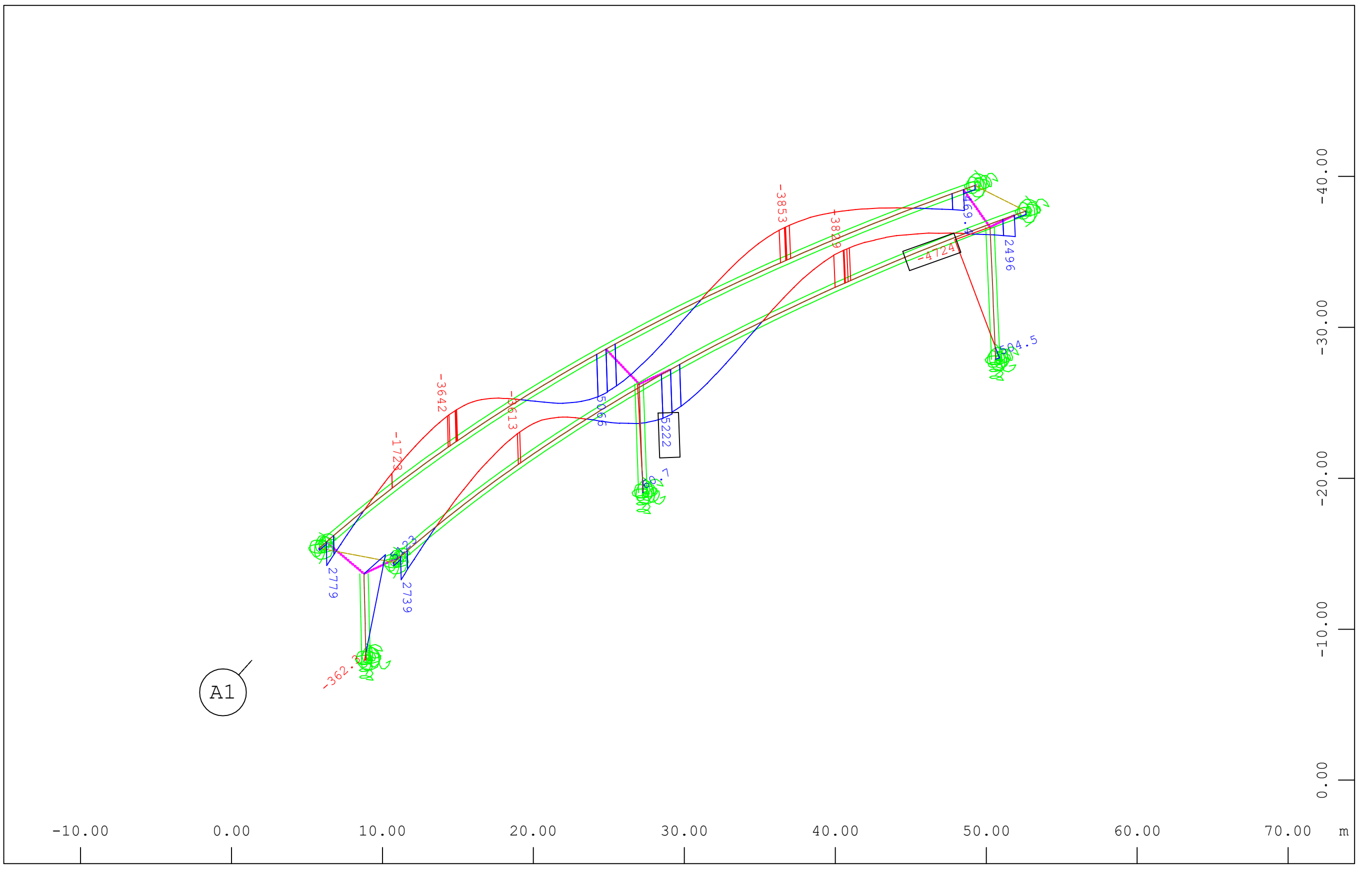
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

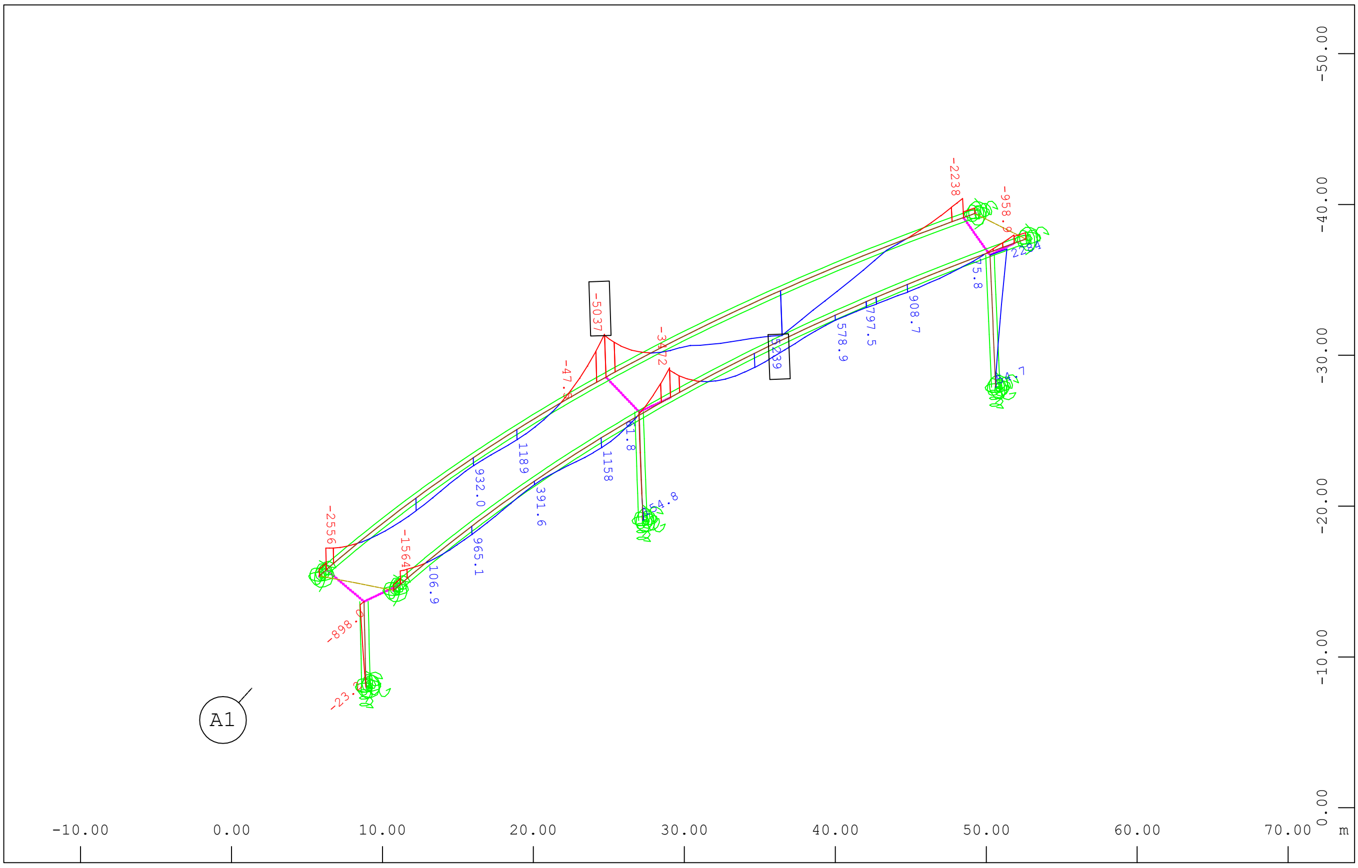
Beam Elements , Bending moment My, Loadcase 2 test case , 1 cm 3D = 8008. kNm
(Min=-4118.) (Max=4550.)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



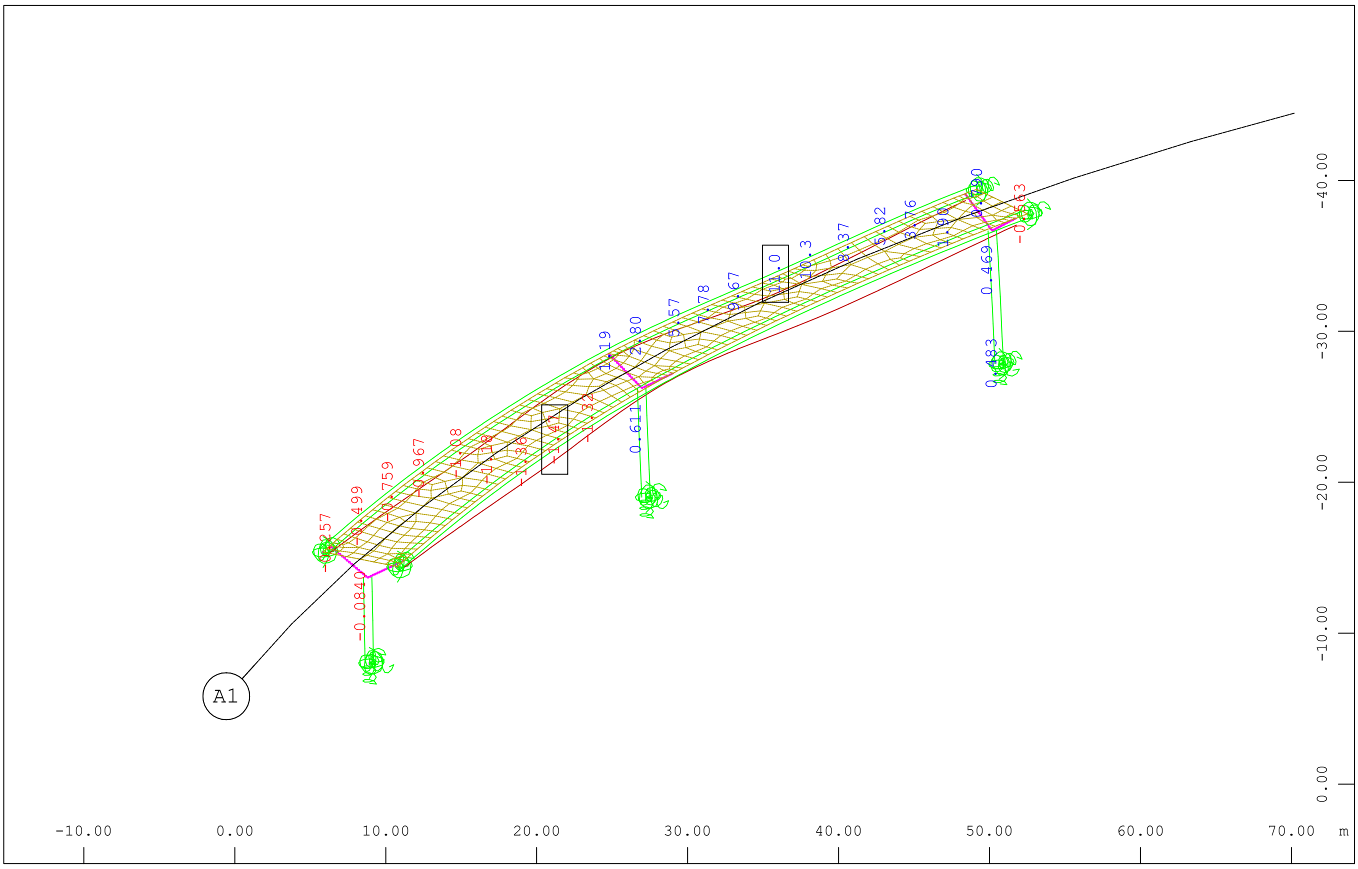
Beam Elements , Bending moment My, Loadcase 3 Curvature loadings , 1 cm 3D = 8008. kNm
(Min=-4724.) (Max=5222.)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



Beam Elements , Bending moment My, Loadcase 229 MAXR-MY BEAM , 1 cm 3D = 8008. kNm
(Min=-5037.) (Max=5239.)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921

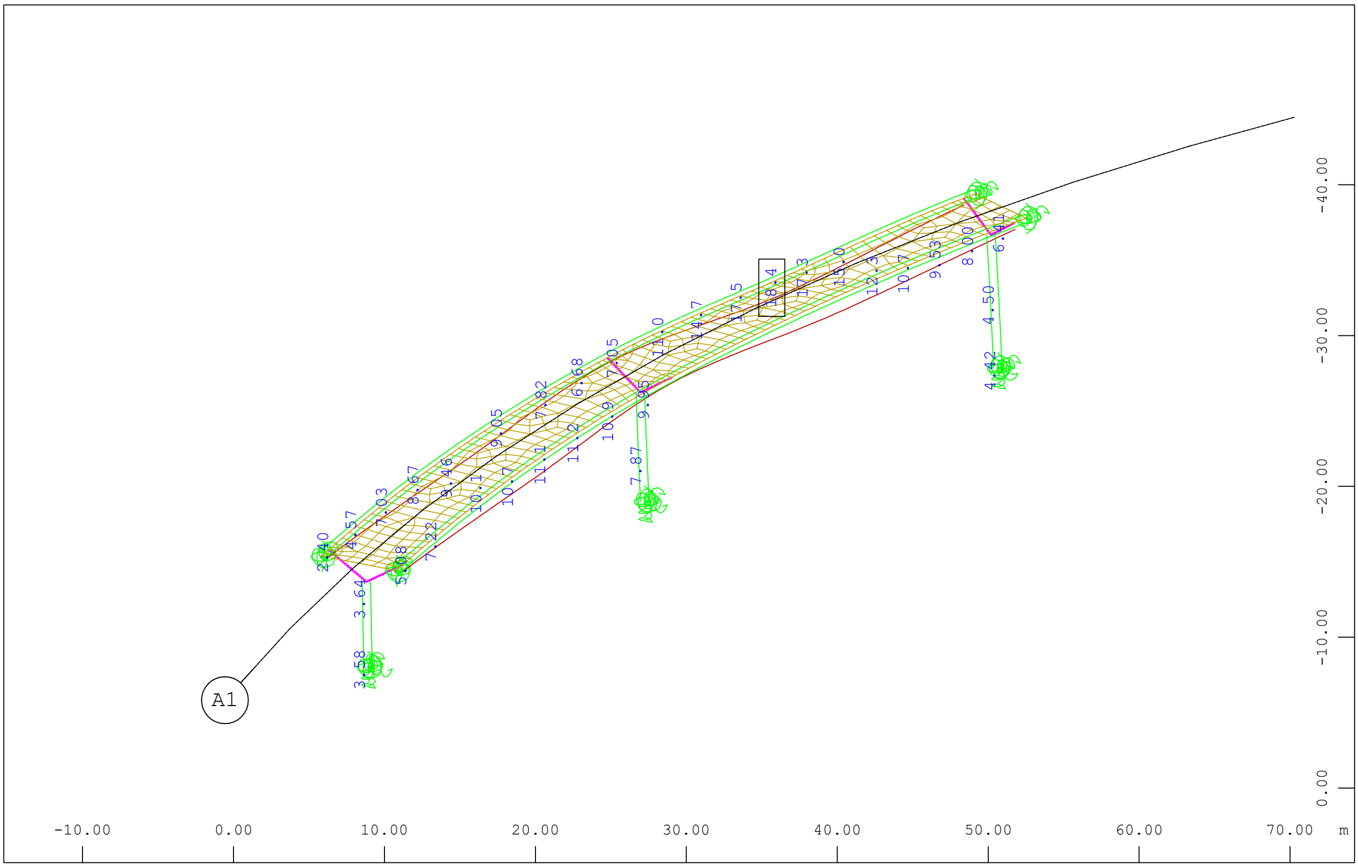


X
Y
Z

Deformed Structure from LC 2 test case Enlarged by 50.0

Nodal displacement in global Z in mm, Loadcase 2 test case (Min=-1.47) (Max=11.0)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921

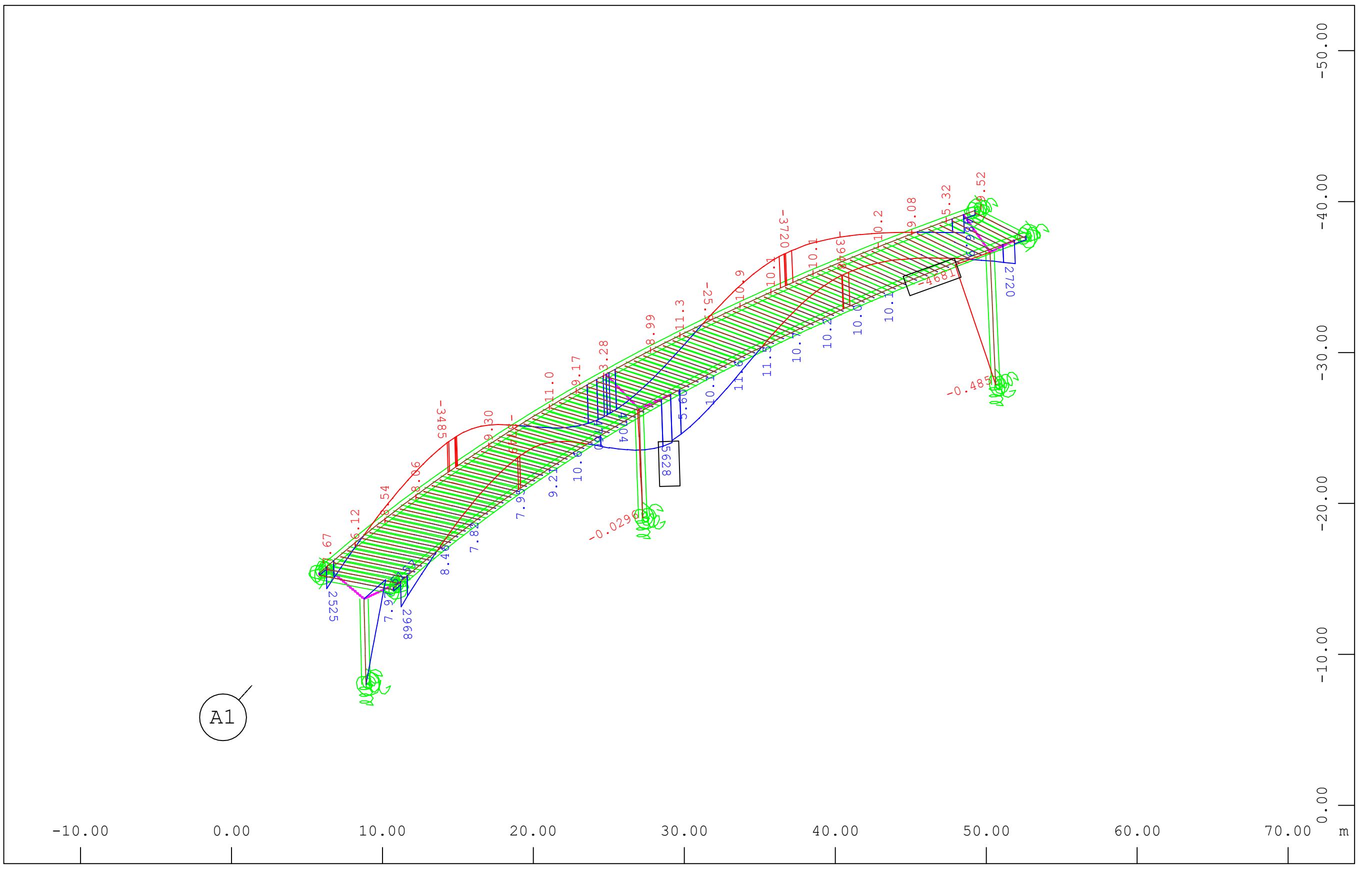


X
Y
Z

Deformed Structure from LC 2 test case Enlarged by 50.0

Nodal displacement in global Z in mm, Loadcase 275 MAXR-UZ NODE (Max=18.4)

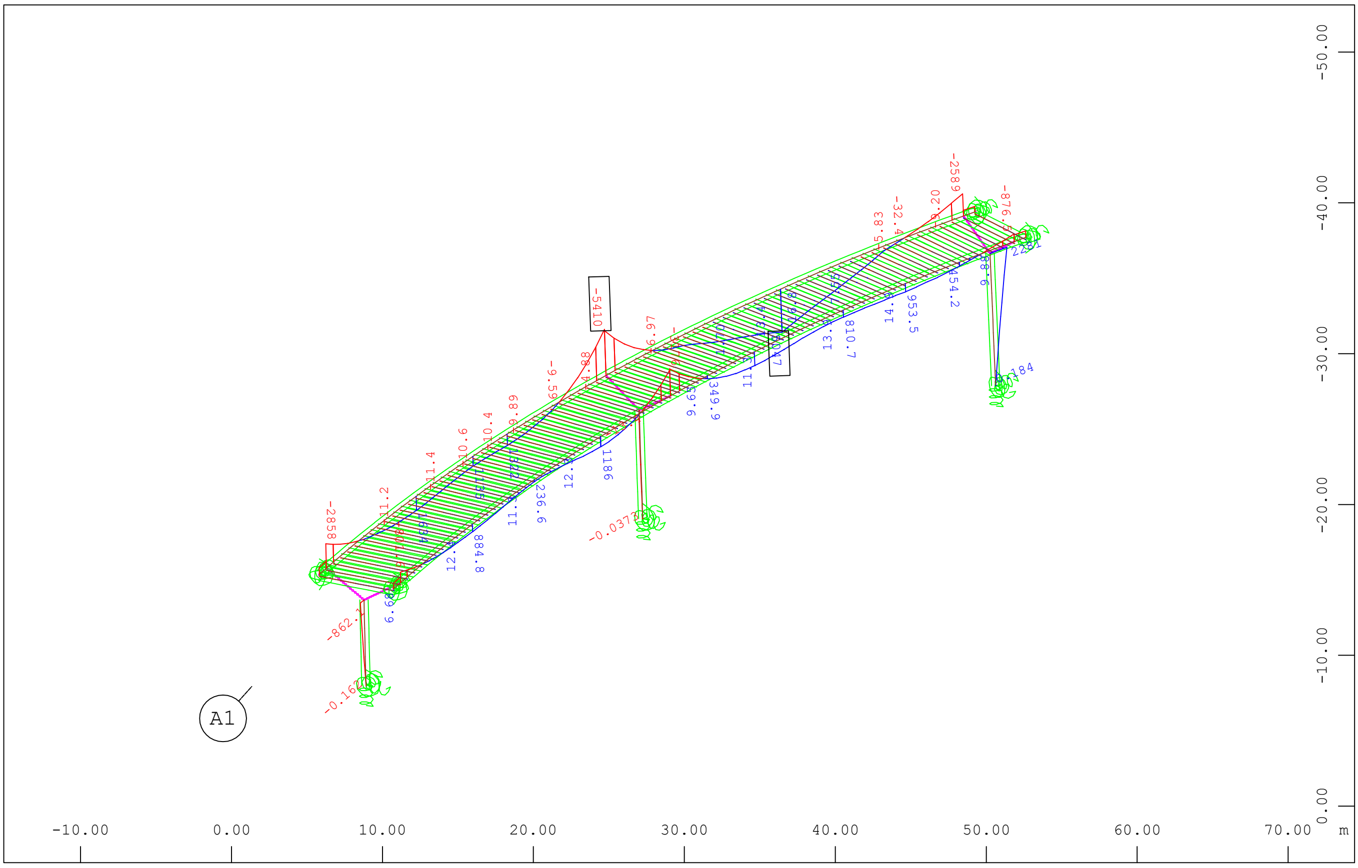
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Beam Elements , Bending moment My, Loadcase 3 Curvature loadings , 1 cm 3D = 8008. kNm
(Min=-4681.) (Max=5628.)

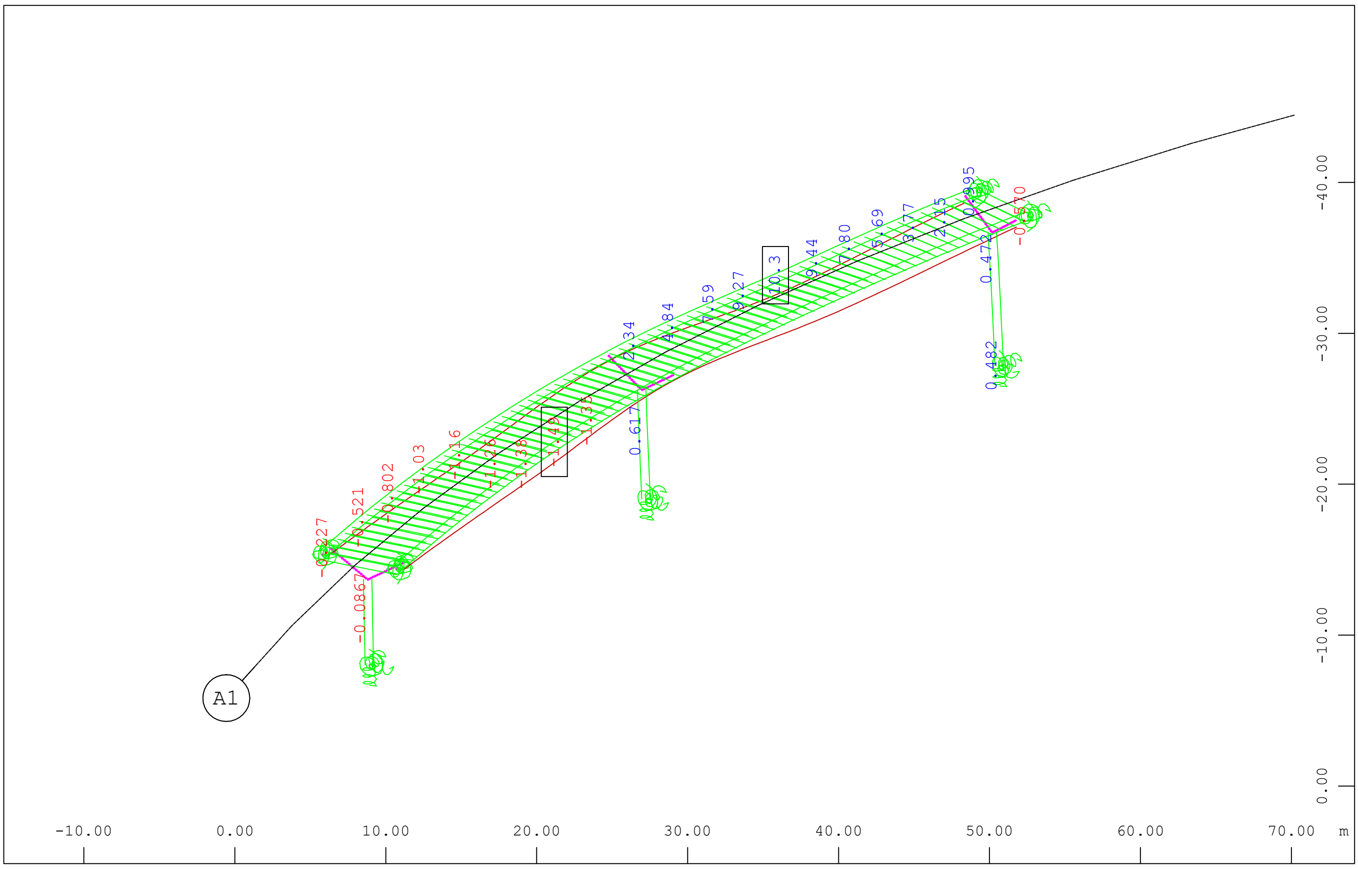
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Beam Elements , Bending moment My, Loadcase 229 MAXR-MY BEAM , 1 cm 3D = 8008. kNm
(Min=-5410.) (Max=5047.)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921

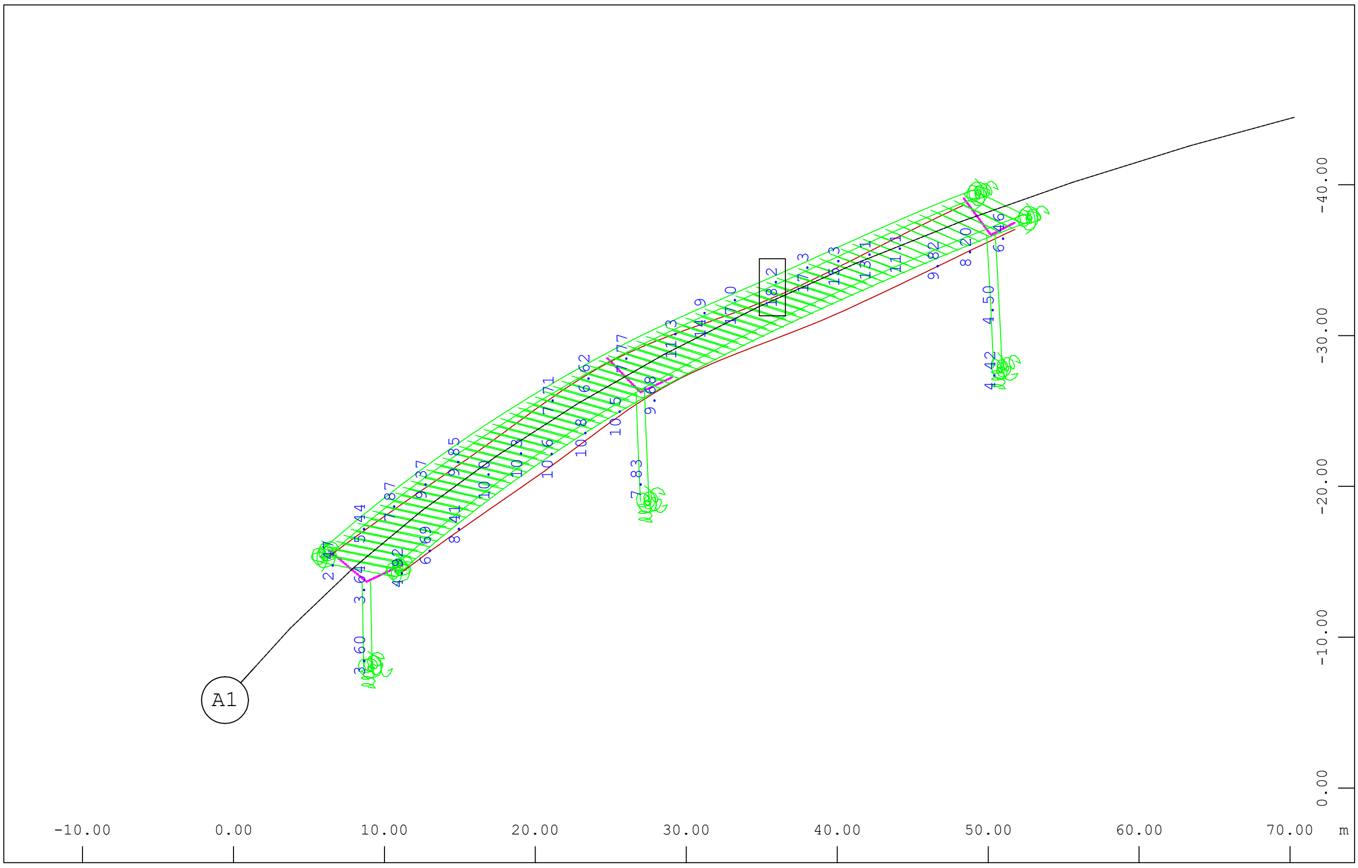


X
Y
Z

Deformed Structure from LC 2 test case Enlarged by 50.0

Nodal displacement in global Z in mm, Loadcase 2 test case (Min=-1.49) (Max=10.3)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921

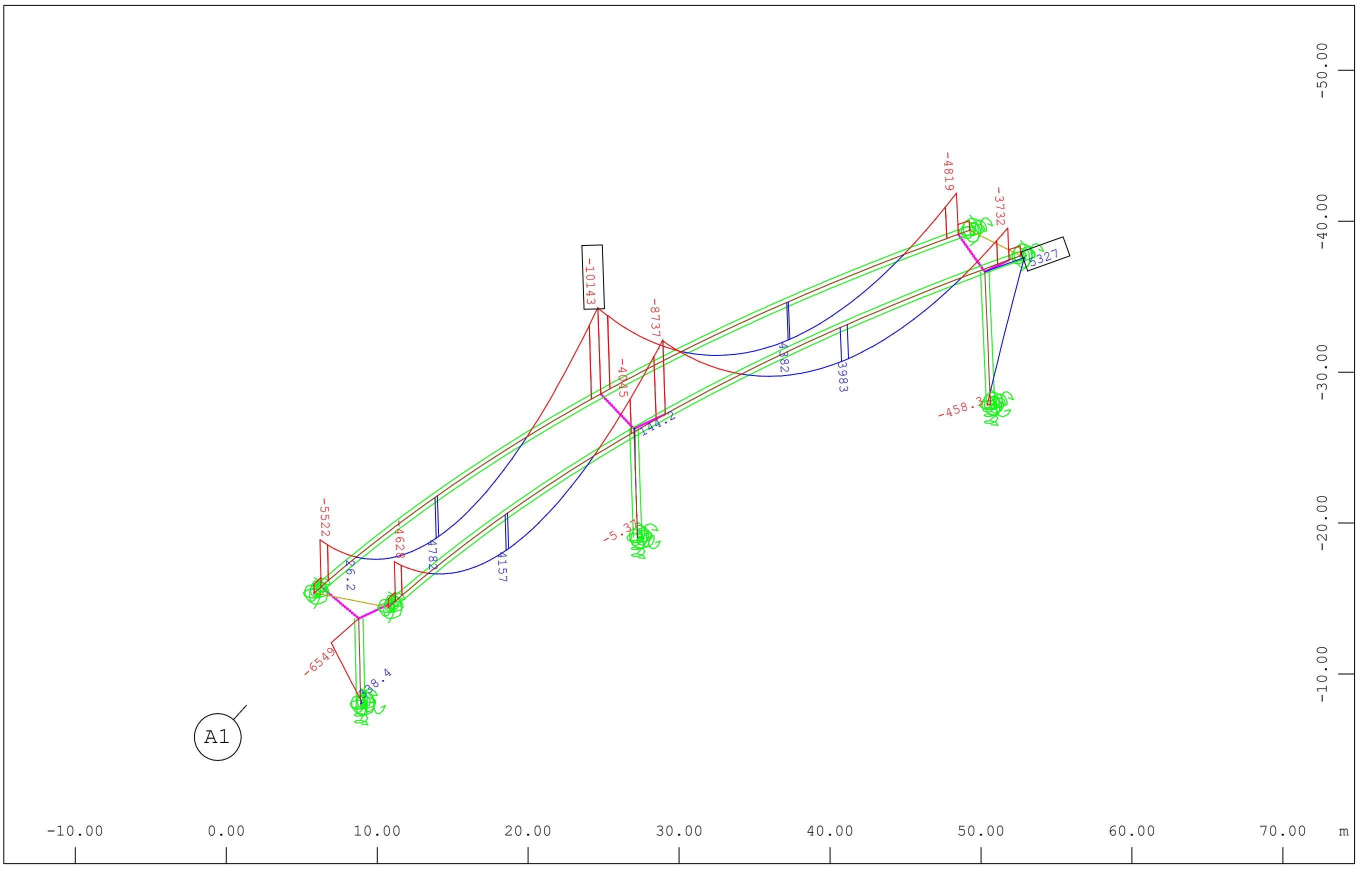


X
Y
Z

Deformed Structure from LC 2 test case Enlarged by 50.0

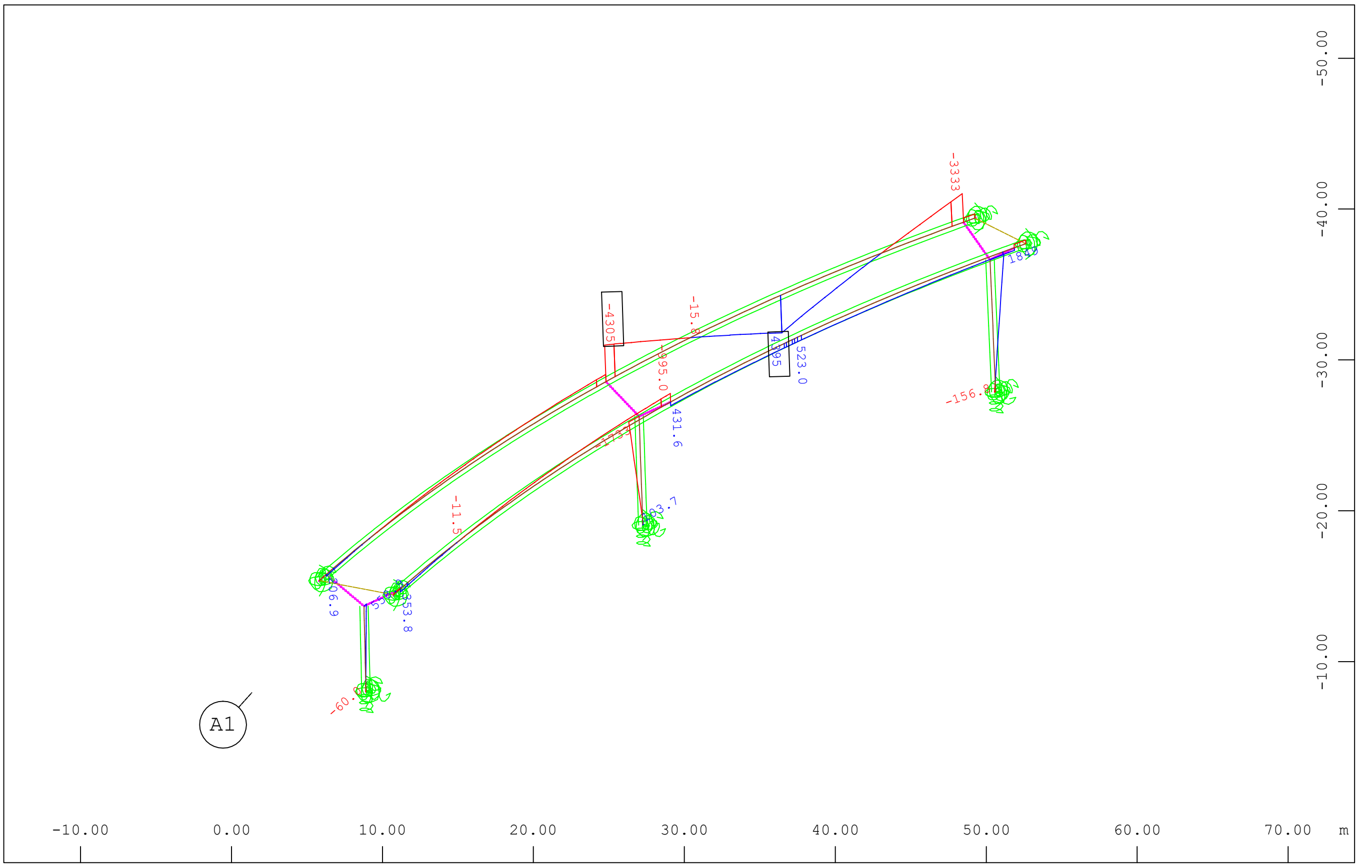
Nodal displacement in global Z in mm, Loadcase 275 MAXR-UZ NODE (Max=18.2)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



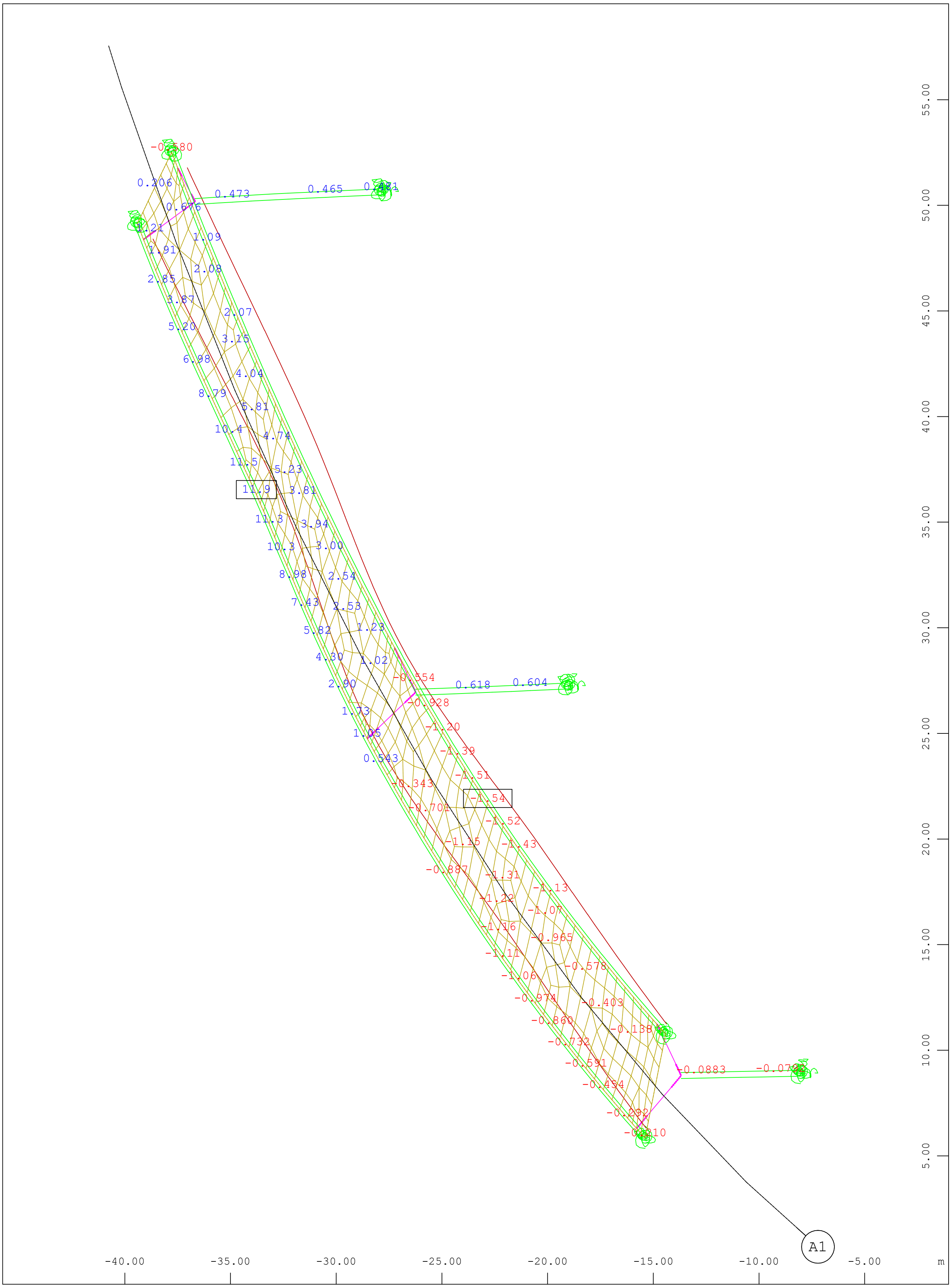
Beam Elements , Bending moment My (Maximum values cubic interpolated), Loadcase 1 dead load , 1 cm 3D = 8008. kNm (Min=-10143.) (Max=5327.)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



Beam Elements , Bending moment My, Loadcase 2 test case , 1 cm 3D = 8008. kNm (Min=-4305.) (Max=4395.)

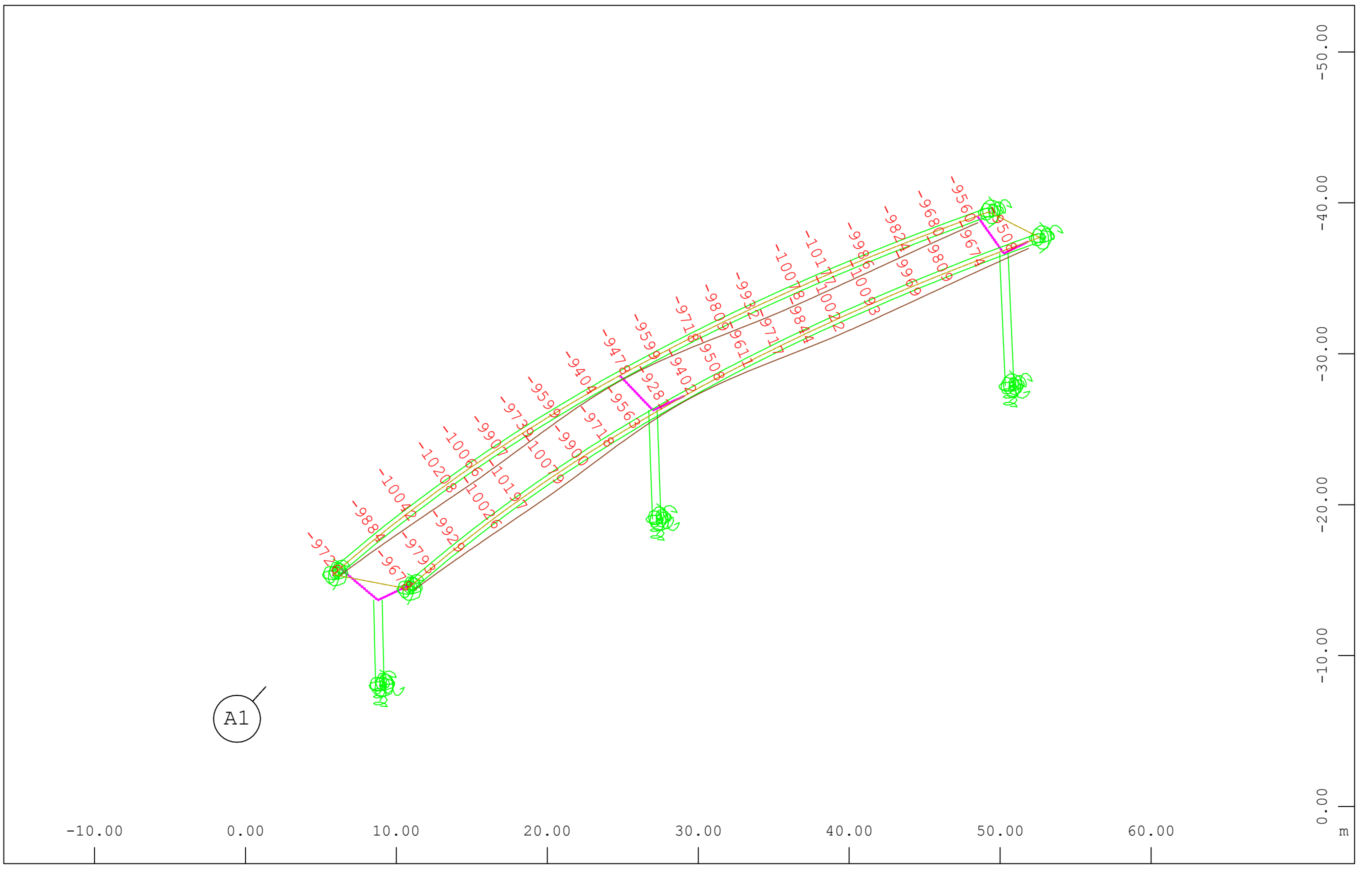
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



Deformed Structure from LC 2 test case Enlarged by 50.0

Nodal displacement in global Z in mm, Loadcase 2 test case (Min=-1.54) (Max=11.9)

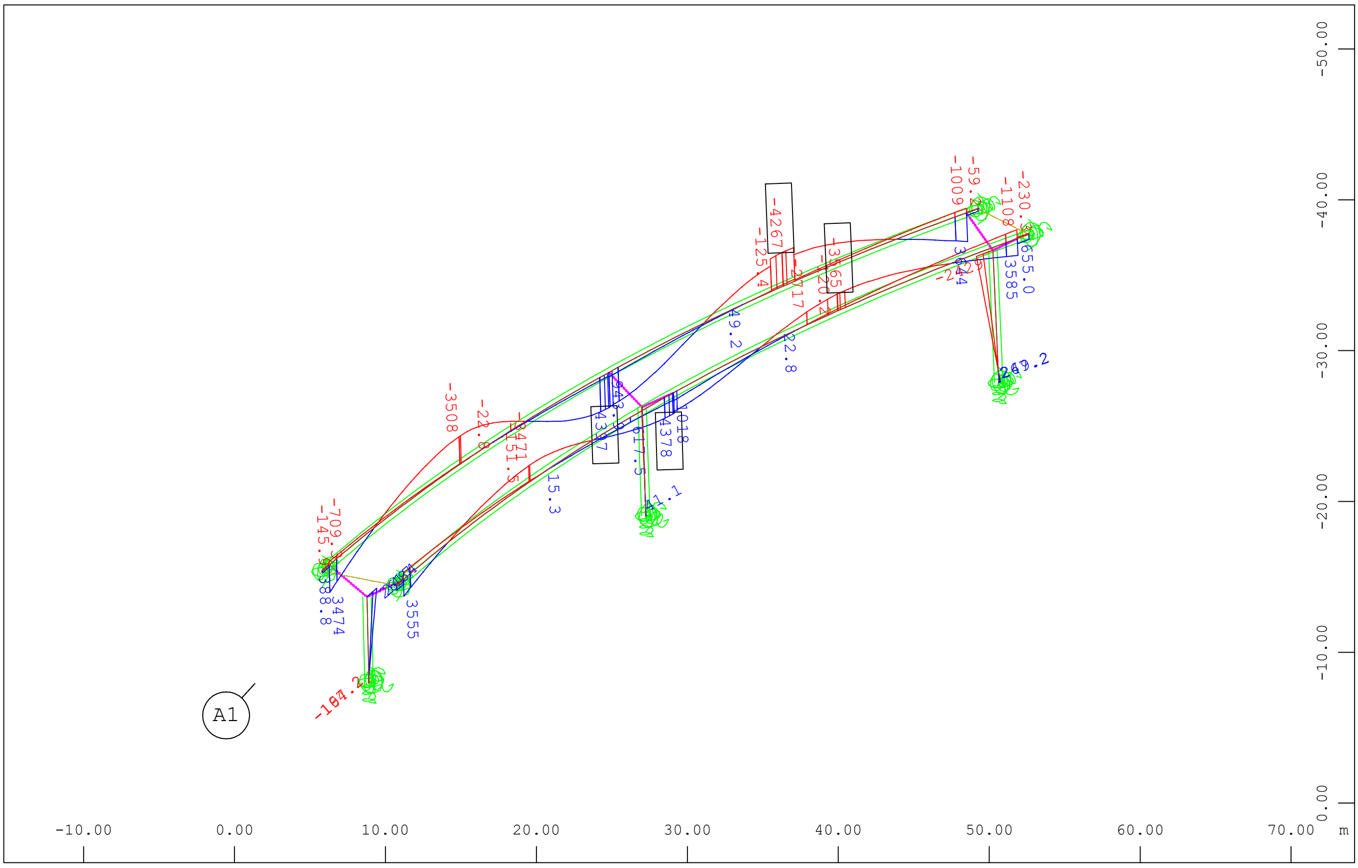
M 1 : 250
X * 0.788
Y * 0.729
Z * 0.921



Beam internal prestress Normal force Nx in kN, Loadcase 3 Curvature loadings
(Min=-10208.) (Max=-9354.)
Beam internal prestress Normal force Nx in kN, Loadcase 4 Curvature loadings

X
Y
Z

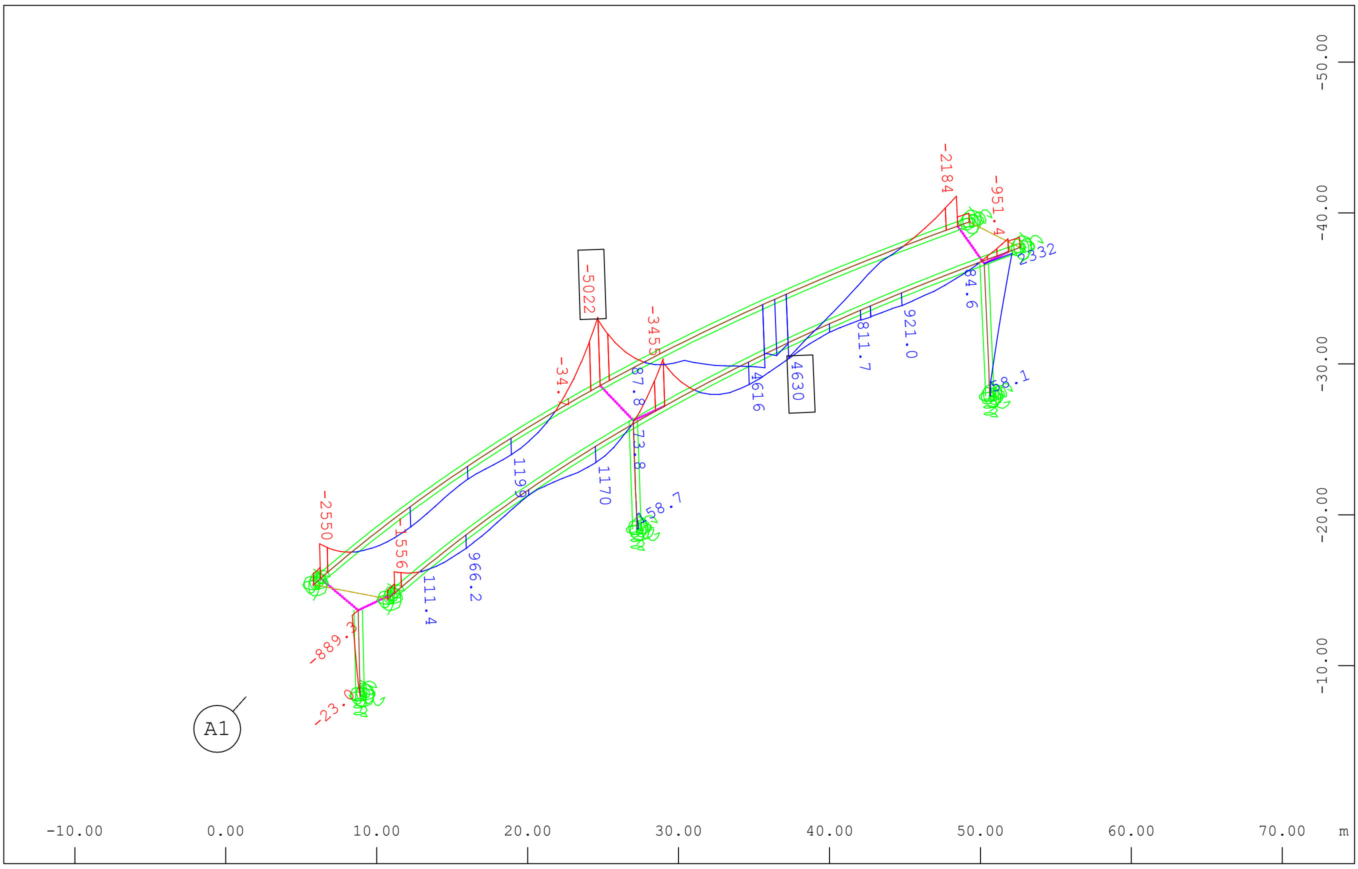
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



Beam Elements , Bending moment My, Loadcase 3 Curvature loadings , 1 cm 3D = 8672. kNm
(Min=-4267.) (Max=4397.)
Beam Elements , Bending moment My, Loadcase 4 Curvature loadings , 1 cm 3D = 14531. kNm

X
Y
Z

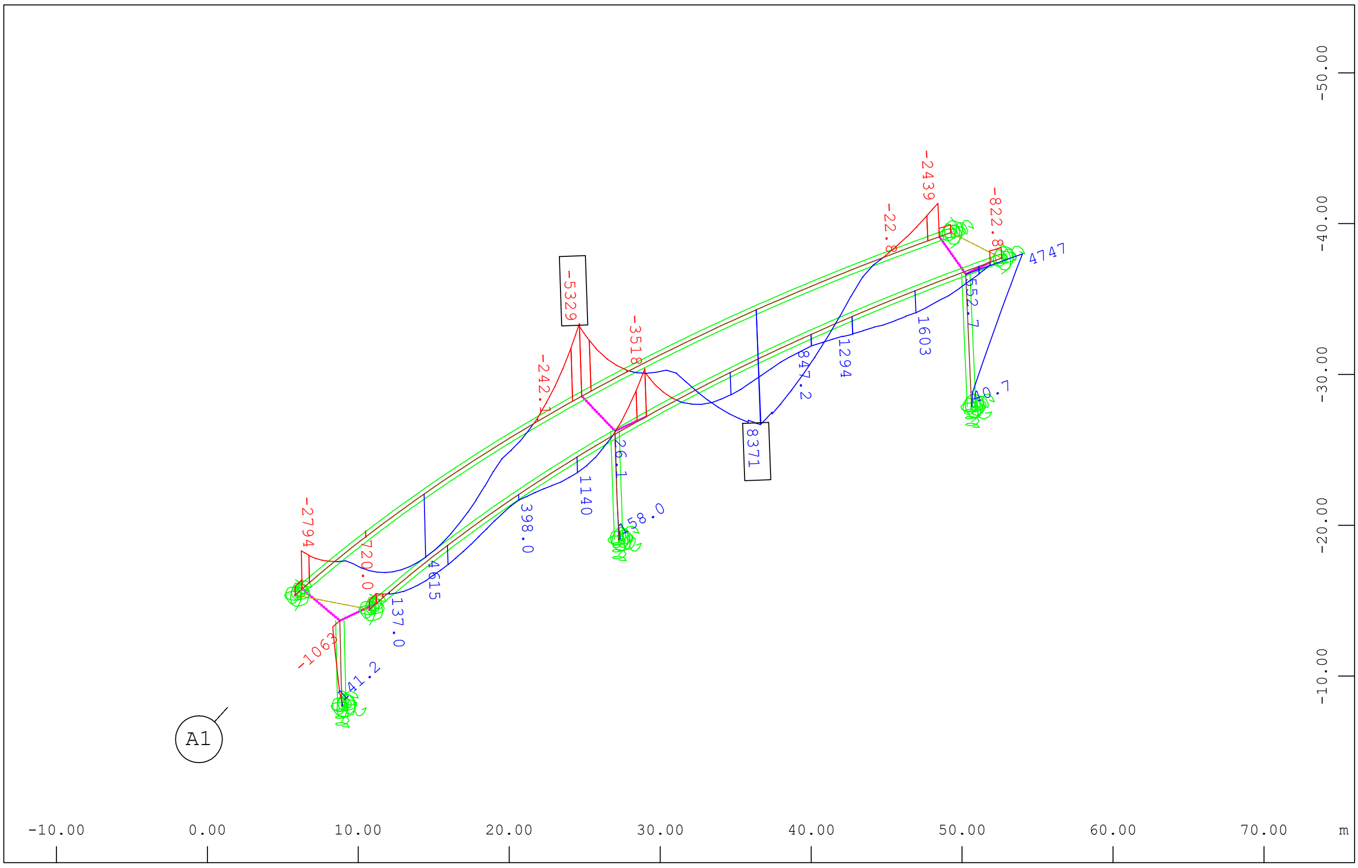
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Beam Elements , Bending moment My, Loadcase 229 MAXR-MY BEAM , 1 cm 3D = 5000. kNm
(Min=-5022.) (Max=4630.)

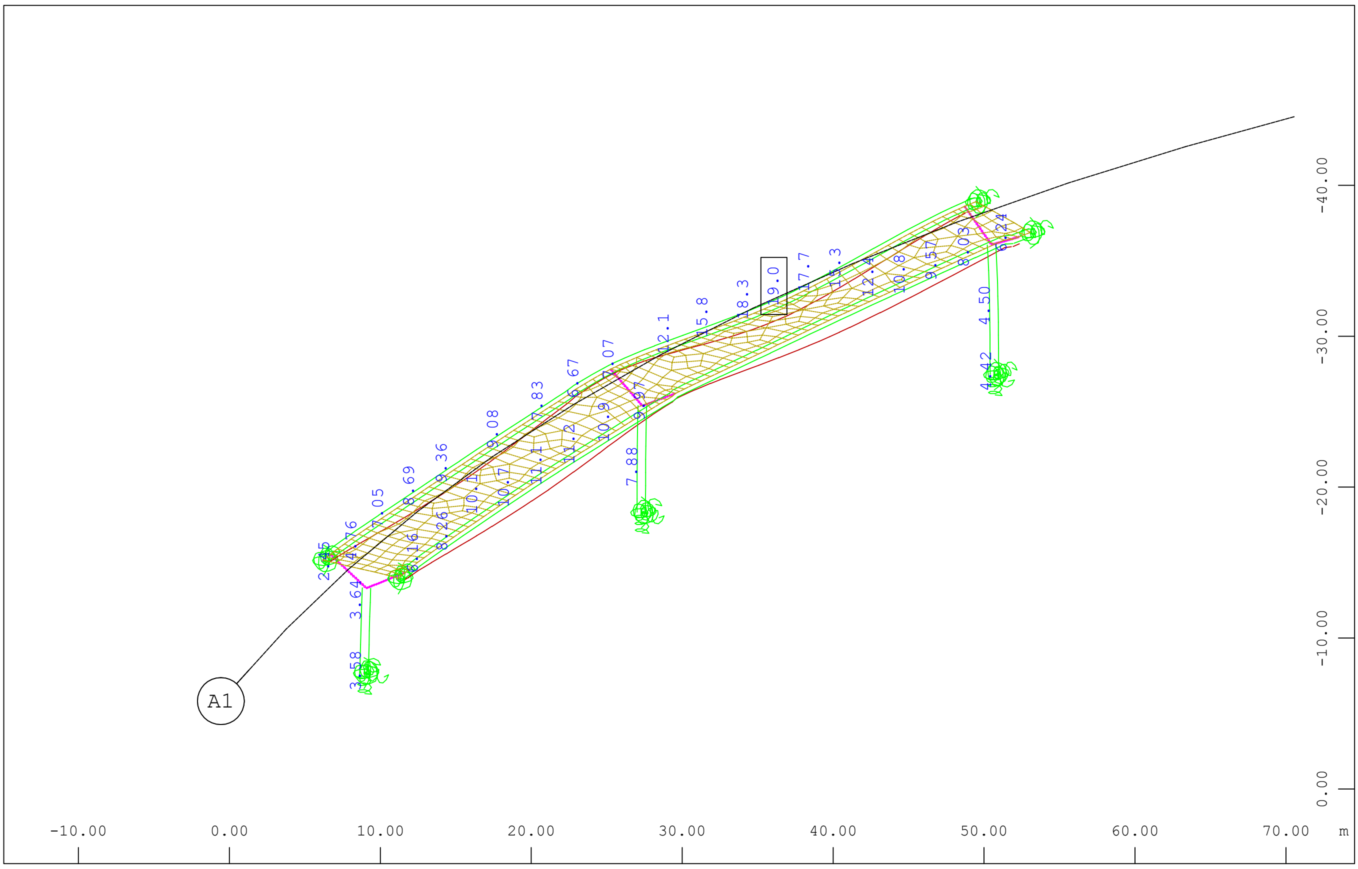
M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Beam Elements , Bending moment My, Loadcase 329 MAXR-MY BEAM , 1 cm 3D = 5000. kNm
(Min=-5329.) (Max=8371.)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921

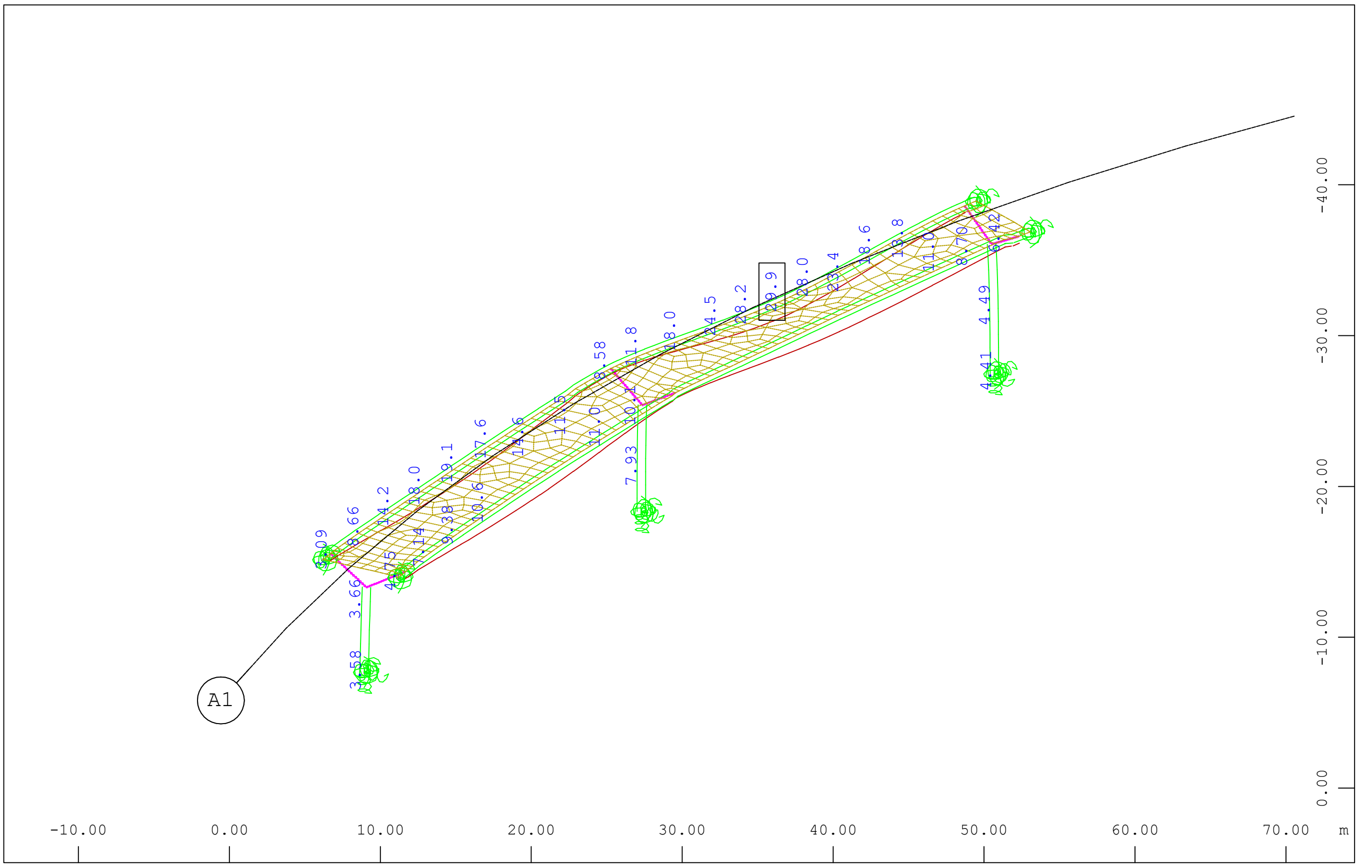


X
Y
Z

Deformed Structure from LC 275 MAXR-UZ NODE Enlarged by 100.0

Nodal displacement in global Z in mm, Loadcase 275 MAXR-UZ NODE (Max=19.0)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921



X
Y
Z

Deformed Structure from LC 275 MAXR-UZ NODE Enlarged by 100.0

Nodal displacement in global Z in mm, Loadcase 375 MAXR-UZ NODE (Max=29.9)

M 1 : 500
X * 0.788
Y * 0.729
Z * 0.921

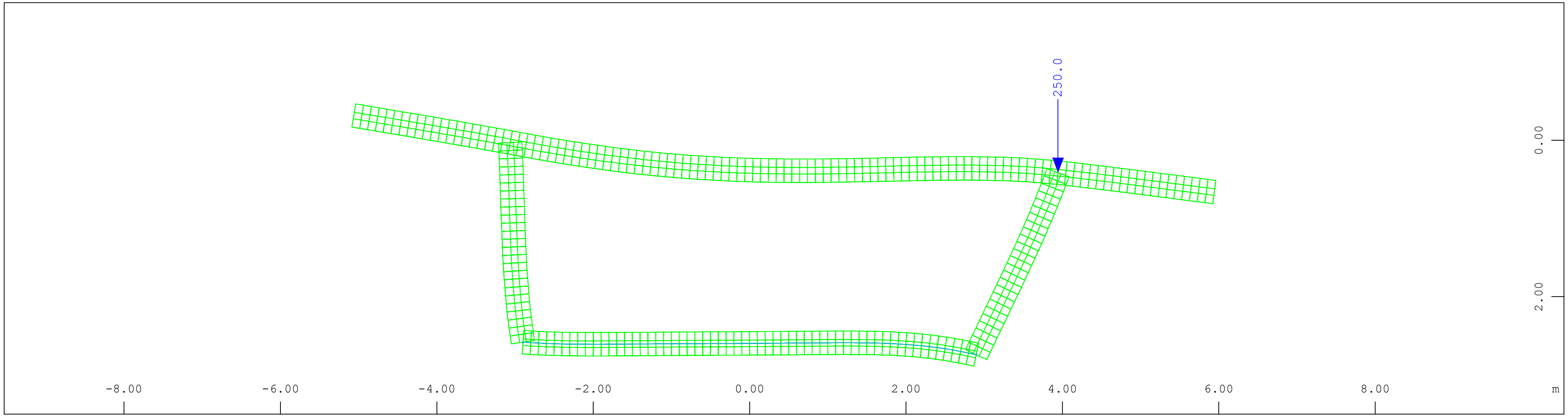
Appendix D

test-section-deformation.dat

test-section-deformation-undamaged.d

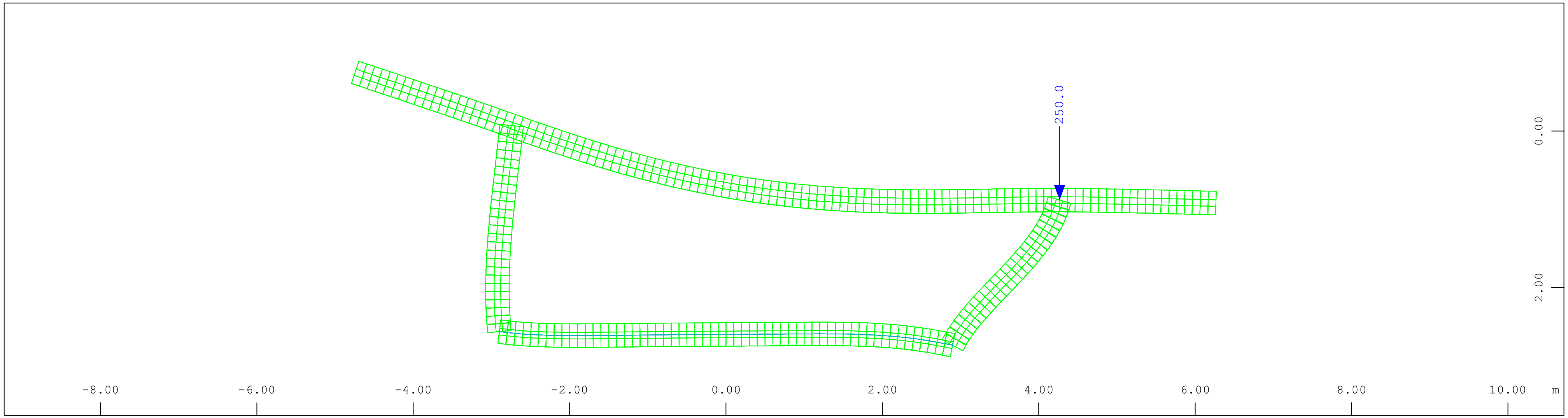
test-section-deformation.gra

test-section-deformation.cdb



Simulation of a hollow girder cross-section
Deformed Structure from LC 101 Ultimate li fact 1.00 Enlarged by 150.0
Cross sections

M 1 : 75



Simulation of a hollow girder cross-section with damaged web
Deformed Structure from LC 101 Ultimate li fact 1.00 Enlarged by 150.0
Cross sections

M 1 : 75

Statutory Declaration

I hereby affirm that the master's thesis at hand is my own written work and that I have used no other sources and aids other than those indicated. All passages, which are quoted from publications or paraphrased from these sources, are indicated as such, i.e. cited, attributed.

This thesis was not submitted in the same or in a substantially similar version, not even partially, to another examination board and was not published elsewhere.

Place, Date	Jan Fröhlich