

Increasing the Reliability and Performance through Automatization and Parallel Working

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Summary

Re-examination of the behaviour of structures can be necessary due to deterioration or changes in the traffic situation during their lifetime. The Finite Element Method (FEM) is widely used in order to accomplish numerical analysis. Considering the development of computer performance, more detailed FEM models can be analyzed, even on site, with mobile computers. To compensate the increasing amount of data needed for the model input, measures need to be taken to save time, by distributing the work. In order to provide consistency to the model, feedback data must be checked upon reception. A local wireless computer network of ultra-portable devices linked together with a computer can provide the coordination necessary for efficient parallel working. Based on a digital model consisting of all data gathered, structural modelling and numerical analysis are performed automatically. Thus, the user is released from the work that can be automatized and the time needed for the overall analysis of a structure is decreased.

1 Introduction

Bridges and buildings are usually designed for given standardized load combinations, according to national and/or international standards^{1,2,3}. These load combinations consider an estimation of future traffic development.

Due to changes in vehicle standardisation and traffic density or in construction state (deterioration), it may be necessary to re-examine the behaviour of the structure under these new conditions. Especially bridges with a long lifetime can undergo such changes several times. The actual development of heavy traffic often exceeds the estimations at the time of construction or the structure itself has to be changed (e.g. enlarging the width of the roadway) to fit again the demands.

Both initial design and re-examination of existing bridges are carried out on an analysis model of the entire structure.

Due to the improvements of modern computers, larger and more detailed models can be generated and computed with the FEM. Instead of superposing results of partial simulations, complete structures can be simulated at once within an acceptable time. Thus, the cost efficiency of the designing process can be increased.

However, the time-consuming part of performing numerical simulations with FEM remains the creation of the analysis model, the data input in a computer program and the verification of the results.

Considering re-examination of existing bridges, especially without having building documents, all necessary data regarding the structure has to be gathered during reconnaissance. Usually teams of three to five members, equipped with special measuring devices (e.g. tachymeter,

Schmidt-Hammer, etc.), measure and collect all relevant structural data on site. Until data processing (after all measurements are done), it is almost impossible to recognize missing or inconsistent data. Therefore, a quality management system is necessary to ensure completeness and consistency of incoming data at the time of acquisition.

Modern computer networking technology is used for establishing a consistent data flow in order to take advantage of:

- portable measurement and computer devices and
- parallel distributed work.

At the University of the Federal Armed Forces Munich, the „Bridge Classification“ project deals with the aspects described in the introduction.

2 Overview of the project „Bridge Classification“

Within the framework of peacekeeping operations of the German Armed Forces one relevant task of the Army Corps of Engineers (Pioniertruppe) is to evaluate the existing infrastructure in the operational area. Especially the load bearing capacity of bridges is important in order to ensure the safety and trafficability of routes.

For this, a methodology is under development to allow an on site determination of the (residual) load bearing capacity of existing bridges. Provided that no building documents of the bridges are available, this methodology includes the reconnaissance of the bridges, their structural modelling and calculations. Input parameters are necessarily the geometry and the material properties.

This paper underlines the aspects of the computer program, named BRIDGE ASSESSMENT CODE (“BRASSCO”), which is under development, for performing the numerical simulations necessary for predicting the admissible load.

The software is designed in such a way that the user is released from almost every work that can be automatized and done by the computer. This includes the assembling and checking of incoming data and the automatic determination of the load bearing capacity of the bridge under investigation.

Section 3 describes the distributed data-gathering interface.

Section 4 gives a brief overview over the automatic structural modelling and the numerical simulations.

3 Distributed Data-Gathering Interface

The data input is a dual mechanism. The data can be entered either at the console (on the laptop with the analysis software) or on remote devices (connected in a local area network, PDA).

The first mechanism (console input) is provided as an easy to use way of entering data (graphical user interface) directly on the computer where the analysis software is deployed. Within the same graphical interface, support is established for the second mechanism. This mechanism permits the collection of data from different team members in parallel. The team leader sends requests to the portable devices (PDA) of the team members, connected in a wireless local area network. The data from the measurements is entered on these devices and transmitted automatically back to the computer of the team leader, which performs the analysis.

3.1 Necessary equipment

The equipment comprises of:

- a powerful computer (the need for mobility usually dictates a laptop) on which the model is generated and the analysis performed. This computer is the server for interlinking all other devices.
- either Tablet PCs or Pocket PCs for the members of the team doing the measurements.
The main characteristic of this equipment is ultra-portability. Touch-sensitive displays replace the keyboard and mouse input and the dimensions of the equipment are reduced.

All devices must be equipped with a wireless network card (preferably built in, so that it occupies a minimum of space).

3.2 Setup of the equipment

The computer (laptop) with the analysis software (BRASSCO) is considered the central node (**team leader computer**). The ultra-portable devices (**team member computers**) are communicating with this central node (messages exchange, data exchange, etc.).

The network to be setup is preferably of “ADHOC” type (i.e. between the network cards of the computers without any additional access point or router equipment). The encryption of the data transfer can be activated, so that no unauthorized person can intercept the data transmitted.

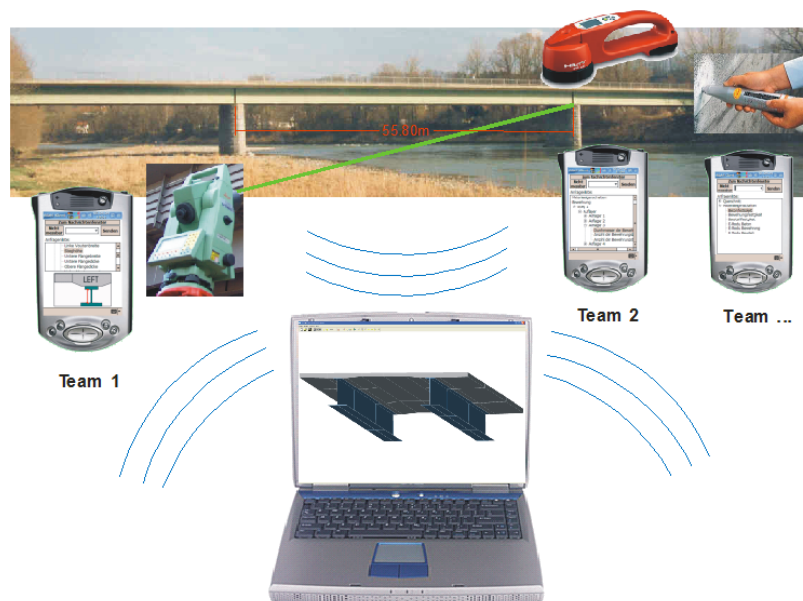


Fig 1: Setup of the hardware devices

3.2.1 Range limitations

All information exchange is piped through the team leader computer in order to provide the best possible range of communication. The program BRASSCO is acting as a message pump, relaying messages to and from the team member computers. According to this setup, the maximum range of communication is considered the distance between one team member portable device and the team leader computer, which still permits the exchange of data.

The wireless devices determine the maximum range limitation (in open spaces typically more than 100 meters without additional antennas, using the current test equipment). Using supplementary antennas (either omni or uni-directional), this range can be increased significantly.

There are however some other limitations, considering mobility and battery lifetime, for the devices, when using supplementary antennas. As always, a compromise must be found between these elements, depending on the situation.

The communication protocol does not require a permanent connection between devices. In case an obstacle reflects or absorbs the radio waves and therefore breaks the connection, it will be automatically re-established. The user is not required to intervene; he has only to monitor the status of the connection, which is displayed on the screen.

3.2.2 Recovery mechanism

A recovery mechanism is in place for the team member computers. Even if they are shutdown (for example to change the depleted battery), they will be acknowledged by the server upon restart and sent all informations necessary (message queue, requests for measurements, etc.). This provides enough continuity for in-field operation, without connection to a power supply, just by switching batteries.

3.3 Communication protocol

The basis for the communication is the network protocol for packets exchange (TCP/IP).

Upon starting BRASSCO on the team leader computer, a listening socket is established waiting for the team member computers to “log in”. Starting the client application on a team member computer, a connection to the listening socket on the team leader computer is established, consisting of:

- message queue (message exchange between team members and team leader)
- request queue (requests are sent from the team leader to the members consisting of a description of what element needs to be measured)

The queues on the server are constantly being updated and connection attempted with the stations addressed by the requests. On connection failure (e.g. station out of range) the request will remain in the queue and connection will be attempted again later. The team leader can monitor which of the team member computers are within range, and which measurements have already been received.

3.4 Interface integration on the team leader computer

On the team leader computer, the task assignment is controlled from the interface of the main program. There is always the alternative to enter the measurement data manually. The team leader can monitor the model parameters together with the status of the data flow. Additionally, visual effects are provided for the elements in the graphical user interface to signal incoming data (figure 2, colour-changed box). This makes it easy for the team leader to keep an overview over the incoming information directly within the graphical user interface.

The data is assembled and transformed in a scaled 3D model visualized on the screen. This geometrical model is used for continuous consistency checks in order to ensure the integrity of the incoming reconnaissance data. In case these checks fail, the user is provided with a detailed error message pointing to the incorrect data or element.

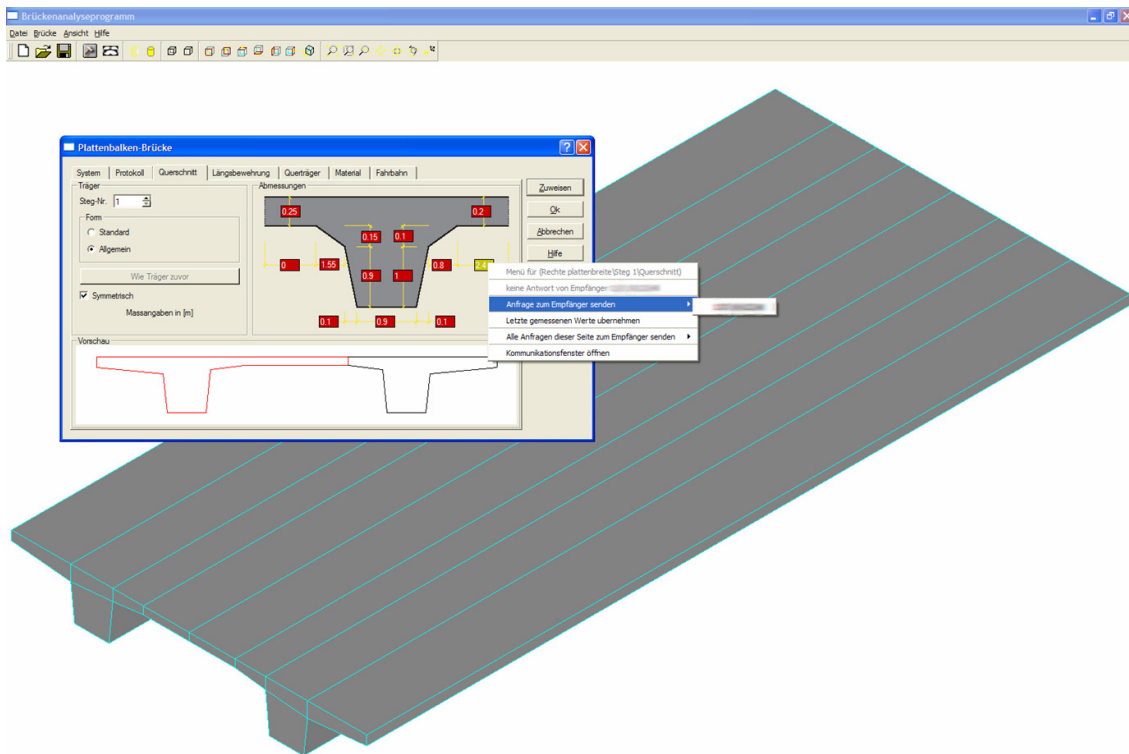


Fig 2: Graphical user interface of the server application and visualization

3.5 The client software on the team member computers



Fig 3a: Tree structure (reinforcement branch)



Fig 3b: Image for cross-section element

The client software is easy to operate through touch screen input methods. The requests are grouped in a tree structure, by the bridge element they belong to (figure 3a). Additional images are associated to some elements (figure 3b) for easier identification. This layout maximizes the efficiency, by optimal use of the available space on the screen. In addition, as on the main computer, a notification system by sound is available for the client application indicating incoming requests.

The message exchange is provided in an other window on the Pocket PC. It consists of a list ordered by the time of arrival so that the user is presented with the most recent information first.

3.6 Ways of employing the wireless communication

The purpose, as stated before, is maximizing the efficiency, by distributing the work, to the maximum extent.

The first use case is assembling small groups, each of them with a different measurement device. For example, we can have a group with a scanner for reinforcement, another one with a tachymeter and one with a Schmidt-Hammer. In this case, measurements can be assigned depending on the type of device needed.

The second use case is when each group is assigned a section of the bridge where they have to do all measurements. This implies each group having all the necessary equipment.

Any combination of manpower and equipment can be used, depending on the situation.

4 Automatic Performing of Analysis

The developed software tool is not used to design bridges. It is used to investigate existing structures. For this, two use cases are implemented.

Firstly, the user can choose typical loading scenarios, e.g. according to the Stanag 2021², within the graphical user interface. The software tool creates all necessary load combinations and superpositions automatically. Performing the verification for all components of the structure the grade of utilization can be determined, and, thus, a decision can be made, whether a vehicle is allowed to pass the bridge or not.

Secondly the maximum admissible load of a given bridge in terms of military load classes (MLC) can be calculated. For this, four loading scenarios are available:

- One way traffic of tracked vehicles
- Two way traffic of tracked vehicles
- One way traffic of wheeled vehicles
- Two way traffic of wheeled vehicles

In both cases, modelling and analysis is treated as a “black box”.

4.1 Data Model

The data model consists of the geometrical information, the material properties and rule based algorithms for creating the structural model. The geometrical information is stored using the BREP (boundary representation). No data condensation occurs.

Thus, the data model can be connected directly to the flow of information, coming in via the distributed data-gathering interface. All informations gathered during reconnaissance are preserved, to be used later on for various discretisations.

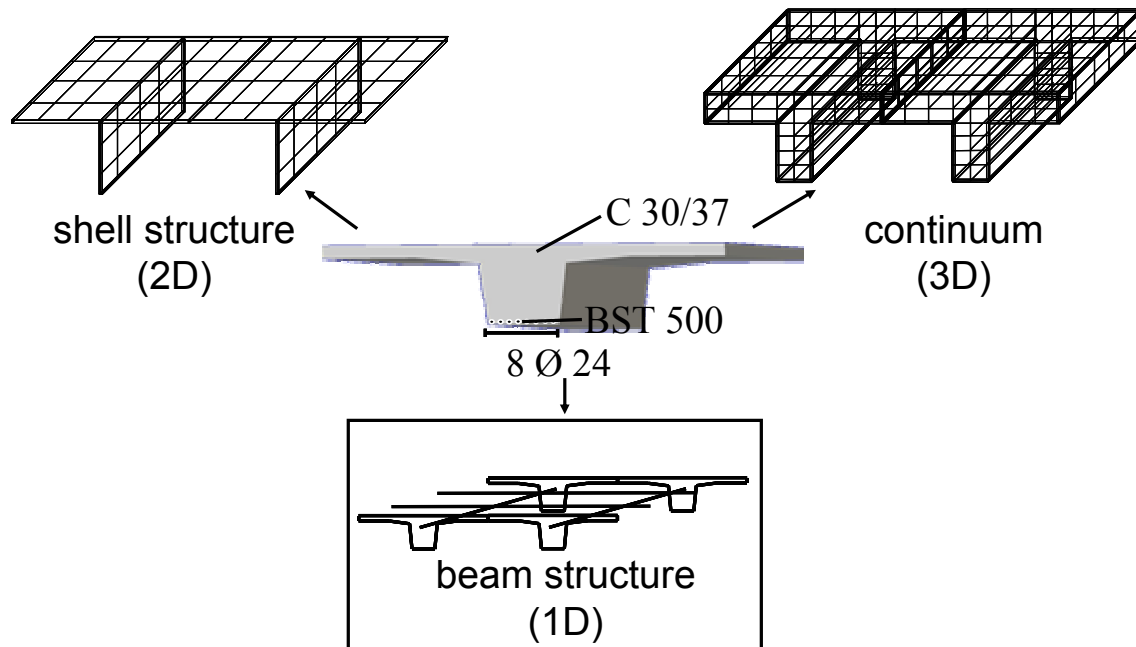


Fig 4: Processing of model

The following section will explain the implemented transformation algorithm for creating a finite element model consisting of beam elements, out of the 3D model.

Approximating the mechanical properties of a bridge with one-dimensional beam elements is on the one hand, sufficiently accurate for predicting the behaviour of most bridges and on the other hand, reduces the calculation time needed for the simulation.

4.2 Creating the 1D structural model

The process of creating the structural model of the bridge consists of two steps.

In the first step, the 3D model is converted into a meta-model, reflecting the topology of the resulting beam structure.

In the second step, beam elements are created on basis of this meta-model and assembled to the finite element model of the bridge.

Creating the meta-model of a bridge depends on the construction type. However, for further treatment of the generated meta-model, the same mechanism can be used. The main task of this mechanism is to condense the 3D information of a component to the uni-dimensional centroidal axis and corresponding cross-sections, according to the Bernoulli hypothesis.

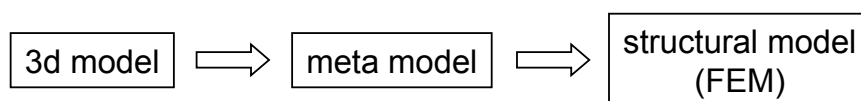


Fig 5: Model transformation

The mechanical parameters (EI , EA , GA , GI) of a volume are described in the principal coordinate system of its cross-sections. These cross-sections are determined by the fact that their

ideal centre of gravity is a point on the centroidal axis and their normal vector is parallel to the tangent vector of the neutral fibre in that point. This determines the origin and one axis of the principal coordinate system. Rotating around this axis with the angle α until the moments of inertia (I_η , I_ζ) are extremums, leads to the principal coordinate system.

$$\frac{dI_\eta(\alpha)}{d\alpha} = 0 \quad \text{bzw.} \quad \frac{dI_\zeta(\alpha)}{d\alpha} = 0 \quad \Leftrightarrow \quad \alpha = \alpha_0 \pm n \cdot \frac{\pi}{2}; \quad n \in \mathbb{N}_0$$

For arbitrary volumes, the determination of the coordinate system of a cross-section decomposes in two steps: In the first step, the centroidal axis has to be determined. In the second step, the cross-sections and their principal coordinate systems are calculated.

The centroidal axis is determined as described above. In addition to pure geometrical algorithms⁴ arbitrary composite components with multiple materials can be treated with this algorithm.

The plane for a cross-section is found analogously to the principal axis by minimizing the area of the cross-section. The angles α and β correspond to the two remaining axis and determine the rotation to find the plane with the minimum area.

$$\frac{\partial A(\beta, \gamma)}{\partial \beta \partial \gamma} = 0 \quad \Leftrightarrow \quad \beta = \beta_0 \pm n \cdot \frac{\pi}{2} \wedge \gamma = \gamma_0 \pm n \cdot \frac{\pi}{2}; \quad n \in \mathbb{N}_0$$

In prismatic bodies ($l \gg b, h$) with sufficient distance to the boundaries, this plane determines a cross-section. Within this cross-section, the principal axis can be determined. The calculated centroids of the cross-sections found, will be interpolated through a B-Spline. The B-Spline is determined by the points of support (centroids) and through the normal vector of the sections. Thus, the amount of necessary cuts can be minimized for a sufficiently accurate approximation of the neutral fibre.

Beams within finite element structures are usually defined by a starting and an ending node with a straight connection between them. Thus, the original curve is approximated by a polygon of the straight elements. The number of elements is determined by the grade of approximation. This grade is controlled by the maximum allowable distance of the approximating polygon from the original curve.

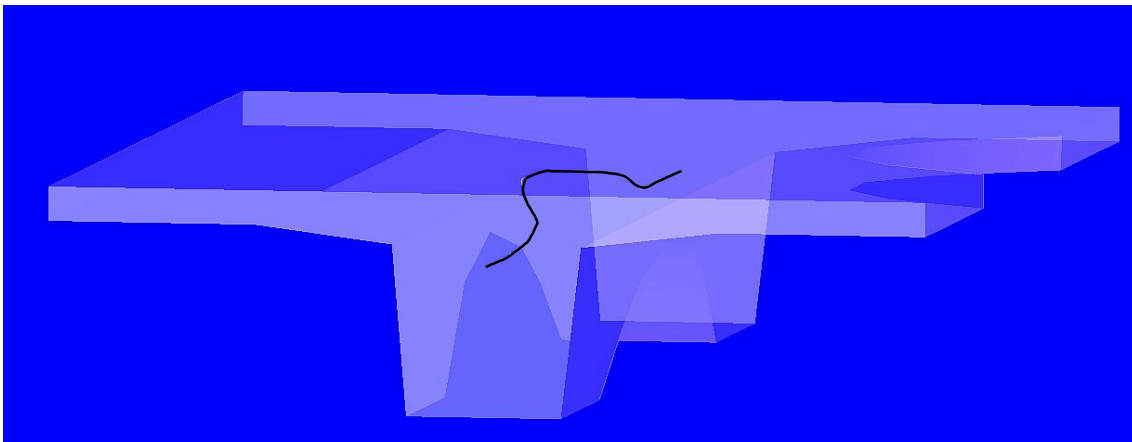


Fig 6: Centroidal axis

Assembling the created beams according to the meta-model, the finite element structure approximating the bridge is created and the distribution of the internal force variables can be calculated.

4.3 Determination of the admissible load

The determination of the admissible load of an existing bridge means finding the greatest load still satisfying the equation:

$$S_d \leq R_d$$

where S_d is the design value of internal variables/stresses due to action and R_d the design value of the structural resistance.

The load patterns for wheeled vehicles according to Stanag 2021² have discontinuous changes in the topology, i.e. number and distances of axes.

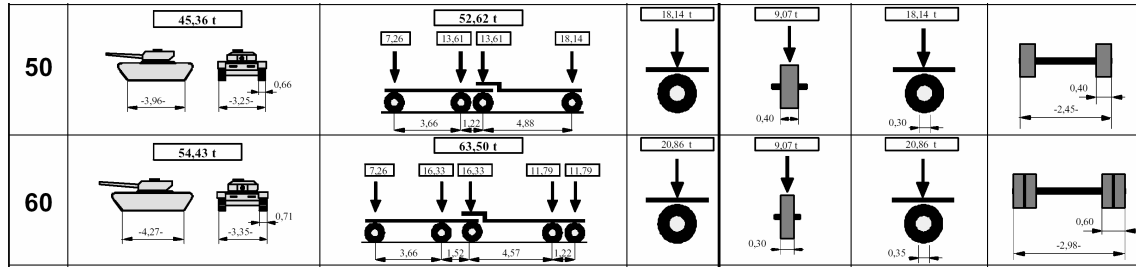


Fig 7: Chart out of STANAG 2021

Examining all loading scenarios described in chapter 4, up to 64 crossings have to be calculated.

This number can be reduced using an iterative algorithm with a linear estimation of the next step, thus decreasing the time needed for calculations. Let U_G be the maximum grade of utilization due to permanent loads and U_{curr} the maximum grade of utilization due to the current load (traffic and permanent loads) then

$$\alpha = \frac{1 - U_G}{U_{curr} - U_G}$$

is an estimation of the increase factor. Multiplying the MLC_{curr} (current MLC) with this increase factor leads to the MLC_{new} of the next step.

The iteration is stopped if the rounded MLC_{new} equals MLC_{curr} .

$$MLC_{new} \approx \alpha \cdot MLC_{curr}$$

On the one hand, the linear estimation reduces the amount of load cases, but, on the other hand, it makes it necessary to determine the maximum grade of utilization for each load case. This is done using a regula-falsi iteration, finding a factor β , for which a given stress resultant $S\{N, T_z, M_y, T_y, M_z, M_T\}$ satisfies the equation

$$\beta \cdot S = S_{max}$$

where S_{max} is a point on the failure surface $g(N, T_z, M_y, T_y, M_z, M_T)$.

Inversion of the minimum β of all beams and corresponding cross-sections, leads to the maximum utilization $U_{\text{curr}}=1/\beta_{\text{min}}$. Especially for nonlinear material properties (e.g. concrete) and large systems, the calculation of β can become relatively time consuming. Therefore, as long as a new S remains within the hyper-cube created by S'_{max} (hatched area in figure 8) the utilization is approximated by the minimum distance of S to the boundaries of the hyper-cube. Only if S lies outside the hyper-cube a new S'_{max} and thus a new β is determined. The new hyper-cube then replaces the old one.

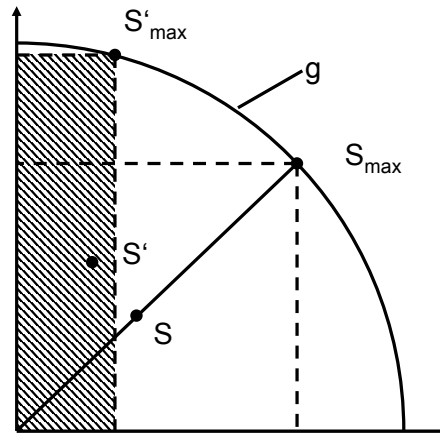


Fig 8: 2D space of internal variable

Therefore, all stored grades of utilization are a lower boundary of the actual utilization. For a proper estimation of the MLC_{new} the actual utilization has to be determined. Starting with the beam with the highest degree of utilization, the actual factor β (and α respectively), is calculated. Within a cycle, we search for the highest utilization, taking the new factor into account. The result of this cycle will constitute the MLC_{new} .

4.4 Results

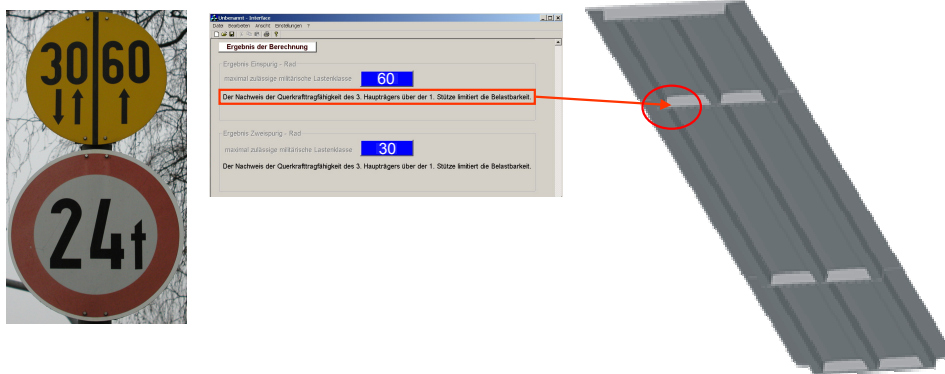


Fig 9: Output of final result (MLC)

Besides displaying the load-bearing capacity of the supporting structure, in terms of MLC or tons, additional information about the bridge is available. A message is posted to inform the user about the weakest component of the bridge. For each calculated load case, information about the structural component that limits the load ability and the failure mechanism is visualized.

In case of damaged bridges, this information is useful for strategies to repair and/or retrofit the bridge.

5 Outlook

There are currently two fields of activity:

- feature recognition for simplification of the geometrical measurements
- assessment of damaged bridges

Many elements need to be measured in order to create a sufficiently accurate geometrical model of a structure. Some of these elements are situated in places where it is difficult for people to operate measuring devices (e.g. girders and cross-girders underneath a bridge's deck).

The development of a feature recognition system is aimed at eliminating the problem of measuring hard accessible elements by means of employing modern tools.

A reference system is established by means of using tachymeters and/or GPS (Global Positioning System). It consists of base points, where the team members can install measuring devices and which are in direct line of sight of the structural elements to be measured. With laser distance gauges and tachymeters, several points on the surfaces of the structure are measured and integrated into the reference system. All data obtained is fed into a software "pre-processor" of the model generation software. Its task is to transform these points into shapes that together form the geometrical model of the bridge.

In order to determine the (residual) load bearing capacity of damaged or deteriorated bridges, the numerical model, on which the analysis is performed, has to be enlarged. Information is kept structured in two layers. In the first layer the reconnaissance data assembled in the 3D model and in the second one the rules for the algorithm responsible for creating the numerical model.

For this, a structure independent damage model will be implemented. In order to keep the direct data flow from the measurement devices to the data model, the fuzzy set theory is used as an approach for directly incorporating uncertainties of damages. This allows not only implementing a damage model based solely on measurable parameters, but furthermore the description of the state of a bridge within human language.

6 Conclusions

The described application for (re-)examination of existing bridges consists of a two-layer architecture. The top layer (data model) is connected to the graphical user interface, processing the data input. The bottom layer (structural modelling) consists of a rule base for transforming the data model in order to perform numerical simulations. A well-defined connection is established between the top and bottom layer. Separating the incoming data flow (and data model) from the analysis model allows enlarging and/or refining the analysis model, by independently adjusting the rule basis. Furthermore, it allows an easy handling of the software program because input data directly corresponds to the measurement devices. Additionally a quality management system ensures consistency of incoming data for the model build-up. Due to this easy handling, field tests have shown an increase in reliability and efficiency using the software tool.

7 References

- [1] European Committee for Standardization: ENV 1991-3, Brussels, 1995.
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