Abstract:
Upgrading of capacity and quality of traffic infrastructure supports maintaining efficiency for growing transportation volumes. Such development is subject of current measures at river Main in order to improve the continuity of the waterway connection between North Sea and Black Sea. Hence bridges have to be revised against design code provisions due to related increased accidental loads of impulse nature. An application of full dynamic analysis of whole bridge structures instead of simplified estimations provides more accurate information in order to minimize needs for structural reinforcement. Different calculation approaches are explained in the article added by some examples of current projects in order to give an impression of benefits of sophisticated calculation procedures that likely differ between new constructions and existing constructions.

Keywords: Ship impact, impulse, equivalent load, dynamic analysis

1 Introduction
Growth of worldwide trade caused an increase of inland waterway transportation. An improvement of waterway infrastructure supports economical and ecological shipping of freight and helps limiting transportation on overcharged roads. The river Main in central Germany together with the 1970 built Main-Danube-Canal constitute the waterway link between Rhine and Danube, both important Trans-European shipping routes. The total length of Main waterway is 384 km between the cities Bamberg and Mainz equipped with 34 locks. 174 kilometers are assigned to the waterway class Vb, whilst 210km fulfill requirements of class Va only (see Table 1) what means that this section is a kind of bottleneck referring to the classification of the adjacent waterways Rhine and Danube including the canal. Therefore an upgrade of the waterway class of this section is proposed until 2010. The main differences between both waterway classes are the length and the total weight of pushing units which both are in class Vb approximately double as large as in class Va (see Table 1).

![Figure 1: CEMT Classes of Main-Sections before 2010 [5]](image-url)

The upgraded tonnage limitation particularly causes a higher risk of severe damage in case of ship collisions with structural members of bridges. While impacts on the superstructure can be easily controlled through height limits collisions with piers cannot be excluded without undesirable restrictions on waterway traffic. The number of ship collisions with bridges throughout Germany in a period from 1991 to 1998 was in average 19 events per year [3]. Therefore all concerned bridges need to be analyzed against impact load of related magnitudes. Since initial calculations with simplifications as equivalent static impact load independent from dynamic interaction and as modeling piers as cantilevers neglecting stiffness an mass of superstructures revealed high costs for reinforcement measures, dynamic time history analyses are requested in order to avoid unnecessary investment on existing bridges as well as costly over dimensioning of new substructures in the future. Such calculations require modeling of the full structure including...
superstructures, bearings and ground properties. The issue of the article is to present the design procedure illustrated with aspects from current examples.

Table 1: Reference values for ship dimensions and dynamic forces for ship impact on inland waterways

<table>
<thead>
<tr>
<th>CEMT-Class</th>
<th>Pushing unit [5]</th>
<th>Length [2] [m]</th>
<th>Width [5] [m]</th>
<th>Mass [2] [t]</th>
<th>$F_{\text{dy}n}^\text{ff}$ [1],[2] [kN]</th>
<th>$F_{\text{dy}n}^\text{fl}$ [1],[2] [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>![image]</td>
<td>80-90</td>
<td>9.5</td>
<td>1000-1500</td>
<td>5000</td>
<td>2500</td>
</tr>
<tr>
<td>Va</td>
<td>![image]</td>
<td>90-110</td>
<td>11.4</td>
<td>1500-3000</td>
<td>8000</td>
<td>3500</td>
</tr>
<tr>
<td>Vb</td>
<td>![image]</td>
<td>110-180</td>
<td>11.4</td>
<td>3000-6000</td>
<td>10000</td>
<td>4000</td>
</tr>
<tr>
<td>VIa</td>
<td>![image]</td>
<td>110-180</td>
<td>22.8</td>
<td>3000-6000</td>
<td>10000</td>
<td>4000</td>
</tr>
<tr>
<td>VIb</td>
<td>![image]</td>
<td>110-190</td>
<td>22.8</td>
<td>6000-12000</td>
<td>14000</td>
<td>5000</td>
</tr>
</tbody>
</table>

2 Design Code Provisions

Coordinated research on ship impact on bridge piers has been established in Germany around 1980 [3]. International design codes did not provide guidance at that time [4]. Ship impact is an interaction phenomenon between a moving impactor and a structure where kinetic energy of the impactor is transformed mainly into deformation energy. Events are mainly characterized by the following circumstances:

- Distance of target from the shipping channel edge (a)
- Impactor mass (m)
- Impactor velocity (v) and impact angle ($\alpha$)
- Stiffness of the impactor (c)
- Momentum and stiffness of the structure
- Stiffness of the foundation

The load model for ship impact relies on physical principles accompanied by probabilistic methods. Dynamic forces of Table 1 are calculated from conservation of energy and momentum for ship types with comparably hard nose constructions however being soft in relation to the target. $F_{\text{dy}n}^\text{ff}$ addresses frontal impact with plastic deformation of the ship body whilst $F_{\text{dy}n}^\text{fl}$ in combination with $F_{\text{dy}n}^\text{fr}$ (see Fig. 2) covers side impact with mainly elastic deformation. Both impact scenarios are analyzed separately. Dynamic forces may be reduced depending on the distance of the shipping channel edge from the pier (see Fig. 2) reflecting influence on the probability of accidents.
Specific dynamic load factors (DLF=$\frac{F_{\text{stat}}}{F_{\text{dyn}}}$) derived from collisions with rigid targets are published in the design code [1], [2] as shown in Figure 3 depending on the magnitude of dynamic forces in order to provide guidance for simple estimations with equivalent static load. Referring to the waterway classes of river Main the dynamic load factor for frontal impact is $\text{DLF}_{\text{F}}=1.3$ and for side impact $\text{DLF}_{\text{S}}=1.7$. For more precise dynamic calculations impact history curves are published in the design codes [1], [2]. All required input data is listed in Table 2 and Table 3 and will be obtained from traffic administration.

Table 2: Elastic impact curve ($F_{\text{dyn}}<5$ MN)

<table>
<thead>
<tr>
<th>$t_r$</th>
<th>$t_a$</th>
<th>$t_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_e = 0.1 \cdot m : c = 60$ MN/m</td>
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</tr>
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</table>

Simultaneous friction impact

$F_{\text{fr}} = 0.4 \cdot F_{\text{dyn}}$

Table 3: Plastic impact curve ($F_{\text{dyn}}>5$ MN)

<table>
<thead>
<tr>
<th>$t_r$</th>
<th>$t_p$</th>
<th>$t_e$</th>
<th>$t_s$</th>
</tr>
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<tbody>
<tr>
<td>$x_e = 0.1 \cdot m : c = 60$ MN/m</td>
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Simplified analysis approaches try to generalize specific structural features making no use of advantageous properties beyond statistically confirmed typical conditions:

- Resilience of the target
- Ground damping
- Structural damping
- Mass inertia
Therefore dynamic calculations are assumed to result in dynamic load factors DLF lower than those for simplified calculation. Best reduction is possible for structural elements with low characteristic frequencies, if impact duration \( t_a \) is much shorter than half of corresponding periods \( T \) (see Fig. 5).

Different approaches for ship impact analysis may be distinguished regarding the number of simplifications (Table 4). Modeling may be performed as cantilever pier (Level 1) or as complete structure (Level 2). Calculation can be done with equivalent static loads (a) or as full time history analysis (b). The selection of an analysis Level depends on the design purpose. In case of review of existing bridges calculation will be performed as step by step procedure.

<table>
<thead>
<tr>
<th>Analysis Methods</th>
<th>Cantilever pier</th>
<th>Bridge structure</th>
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<tbody>
<tr>
<td>Static calculation</td>
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<tr>
<td>Level 1a</td>
<td><img src="diagram1" alt="Static Level 1a diagram" /></td>
<td><img src="diagram2" alt="Static Level 2a diagram" /></td>
</tr>
<tr>
<td>Level 1b</td>
<td><img src="diagram3" alt="Dynamic Level 1b diagram" /></td>
<td><img src="diagram4" alt="Dynamic Level 2b diagram" /></td>
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<tr>
<td>Dynamic calculation</td>
<td></td>
<td></td>
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</tbody>
</table>

Level 1 reduces the structure to cantilever piers neglecting lateral support provided by the superstructure and delivers worst magnitudes of reaction forces and moments. The substructure consisting of the pier including foundation must fulfill all requirements in the ultimate limit state:

- Bearing capacity of structural members
- Ground strength
- Overturning stability
- Sliding stability

Dynamic calculation of cantilever piers might result in a slight reduction of reactions mainly depending on stiffness and damping properties of the structural system and the underground. Typical bearing configurations provide lateral support for the superstructure but often no longitudinal support. That means Level 1 analysis is often fully appropriate for lateral impact.
In case of short piers possibly significant portions of dynamic forces are transferred into the superstructure and can cause damage to bearings. A Level 2 analysis is recommended. If there is some lateral support available on top of piers Level 2 analysis provides more realistic forces and moments. Due to the statiscal indetermined system stiffness properties especially of the ground must be considered with their upper and lower boundary values (see Table 4). The stiffness of the superstructure should be covered through modeling the whole structure in order to cover response of adjacent piers. P-Δ-effects should be considered.

3 Examples

One example for a technical review of pier performance against impact load of an existing bridge is shown in Fig. 6 and Fig. 7. This bridge was extended with a complete new second bridge construction in order to provide separate roadways for both traffic directions. The steel bridge features a comparably large clear span of 138m with nevertheless one pier in the water. The superstructure is laterally fixed to the pier whilst no longitudinal fixing is available due to thermal dilatation. Piers consist of concrete (see Fig. 8) with sparse steel mesh causing crack moment being higher than bending capacity.

Initial calculations for a cantilever structure with equivalent static loads (Fig. 8) resulted in a satisfying performance against frontal impact with only minor shortcomings in sliding stability. No reinforcement has been proposed due to a protection by the adjacent pier of the new bridge that was fully designed against ship impact or rather lateral support by that pier. Simplified calculations for flange impact resulted in minor deficiencies in ground strength, overturning stability and bearing capacity of the pier which require some reinforcement measures. Reasons for differences in performance for both force directions might be that the pier was originally designed against significant wind forces parallel to the frontal impact while no forces except from bearing friction were originally analyzed parallel to the side impact.

Figure 6: Ebertbrücke

Figure 7: Site plan

Figure 8: Pier dimensions with labeling of dynamic load
Dynamic analyses were executed with a finite element model using shell elements for the steel superstructure and volume elements for the piers. Soil properties were modeled as spring elements. Most important parameters are ground stiffness and viscous damping. Ground stiffness was calculated with 100 MPa as lower limit and 300 MPa as upper limit in accordance with site survey report. The lower limit of damping ratio was assessed as 2% referring to DIN 1055-4:2005. This value corresponds to earthquake provisions of DIN EN 1998-2:2006 for non cracked concrete. The upper limit for damping was adopted from the earth-quake code with 5% for cracked concrete even though the existing reinforcement ratio does not allow significant cracking.

The impact curve for the front collision is shown in Fig. 11. Calculation results for bending moments at foundation top as example are contained in Fig. 13. These diagrams depict dynamic reactions dependent from time for different boundary conditions. Values of corresponding static calculation are marked with a red line. Reductions in comparison to static calculation are significantly depending on the damping ratio. Maximum reduction results from stiff ground with high damping in an order of 25% however values for lower damping are deemed to be more adequate for design purposes. Around 5% damping assumes a mostly fading of vibration before peak dynamic force is reached (Fig. 13) so initial punch would represent the maximum response. Specific for this bridge lateral support forces of the superstructure are almost negligible due to the large span and local elastic deformation capacities. Otherwise larger reductions could be gained.
The impact curve for the lateral collision is shown in Fig. 12. Calculations were performed including friction components. A reduction of horizontal reaction forces was found with 16% for stiff ground with low damping (see Fig. 14). For both analyzed ground stiffnesses impact duration is shorter than one half period, promising beneficial reductions or response forces.

Since full structure models do not fully comply with association of single degree of freedom swingers (SDOF) influence on dynamic response may differ between diverse types of response (e.g. moment, horizontal support). A transfer of calculation results on other piers or on other buildings is not possible.

Examinations of an existing concrete bridge (Figure 15, Figure 16) are presented as further example. This bridge was originally designed for ship impact with static equivalent loads much smaller than current design code requirements.
Characteristic features of that structure are comparably slender piers in conjunction with a stiff superstructure (Fig. 17 to Fig. 19). Piers rest on pad foundations. Initial Level 1 calculations with equivalent static load indicated that either protective devices needed to be installed or structural reinforcement was necessary for foundations and piers.

A feasibility study [5] exposed high potential for savings through full dynamic Level 2 analysis due to reductions of response forces in comparison with static Level 1 procedure. However exigency of upgrading still remained including superstructure and bearings due large top support reactions hardly to resist. During step by step preliminary design of structural fortification beginning from foundation and piers stiffness relations significantly shifted counteracting efforts to reduce structural response. However approaching achievement of overturn stability criteria spent evidence for the chance to redistribute response with just little over sizing of foundation in order to desirably avoid intervention to the superstructure and bearings. Finally advantages of full dynamic Level 2 analysis were found to be smaller than preliminary analysis of the existing structure indicated. However simplified Level 1 analysis would have led to a less economical design.

Another example is the design review of a complete new bridge construction of pre-stressed concrete with a similar layout as described in the latter example (Fig. 20). Piers will be equipped with a deep foundation reflecting poor ground conditions. Bearings including anchorage are designed for a full lateral top support in order to transfer portions of ship impact pulse towards adjacent piers. The evaluation of Level 2 results against simplified Level 1 design resulted in considerable capacity reserves within that construction project encouraging the authors to recommend full dynamic Level 2 analysis for design projects in the future.
4 Conclusion
Upgrade of traffic infrastructure due to increasing passenger transport und freight shipping requires reviews of buildings like bridges concerning related loads. In case of the addressed Main section as part of an international inland waterway a number of bridges had to be evaluated against new design code provisions. Experience from planning of new bridges exposed that application of full dynamic analysis of the whole structures against ship impact provides more accurate information of related response in order to enable an economical design. Reviews of existing bridges aim at minimum reinforcement work. Hence sophisticated calculation methods appear to be supportive to avoid unnecessary intervention to older constructions. In general savings can be gained for existing bridges as presented in some examples. However restrictions like bearing capacity of single components or accessibility for reinforcement might enforce technical solutions that expose smaller benefits of such calculation methods. A dispense of expected reinforcement need by means of more detailed calculations may be anticipated if results of initial estimations are not too far beyond code provisions.

5 References
[4] Biehl, Florian; Kunz, Claus - Ship Bridge Collision in River Traffic - Simulation and Derivation of Load - Deformation Relations, 2005