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Structural Design to Resist Impact

Conception de structures résistant aux chocs

Aufprallsicherer Entwurf und Konstruktion

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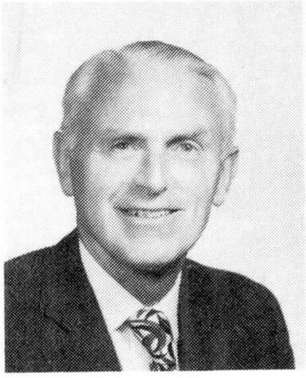

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SUMMARY
A bridge pier, under impact loading from a ship collision, exhibits a dynamic response and, in conjunction with the foundation, is the ultimate participant in the energy absorption equation. The capacity of this pier foundation system to resist the impact in a ductile fashion can be significantly enhanced at moderate cost by selecting an appropriate configuration for the pier base, proper reinforcement for pier shafts, and sand or concrete fill of hollow piling, and by providing adequate bearing support and restrainers for superstructure connection to the pier cap girder.

RÉSUMÉ
Soumise à une charge d'impact provenant de la collision d'un navire, une pile de pont produit une réaction dynamique, et, associée aux fondations, participe en dernier lieu à l'équation d'absorption d'énergie. La capacité des fondations de la pile à résister aux chocs de manière ductile peut être sensiblement améliorée à bon marché en choisissant la configuration appropriée à la base de la pile, en renforçant correctement les piliers, ainsi qu'en fournissant des supports et retenues appropriés au raccord de la superstructure joignant la partie supérieure de la pile.

ZUSAMMENFASSUNG
Ein Brückenpfeiler weist beim Aufprall durch einen Schiffskörper eine dynamische Reaktion auf und ist, in Verbindung mit dem Fundament, der elementare Bestandteil in der Gleichung der Energieabsorption. Die Fähigkeit dieses Pfeilerfundamentes, einem Aufprall in nachgiebiger Weise zu widerstehen, kann bei geringen Kosten erheblich verbessert werden, indem eine geeignete Konfiguration für die Pfeilergrundlage, eine angemessene Verstärkung der Pfeiler sowie eine Sand- oder Betonfüllung für Hohlräume ausgewählt, und außerdem geeignete Lagerungen und Verstrebungen für die Hochbauverbindung zum Pfeilerträger vorgesehen werden.

1. STRUCTURAL DESIGN TO RESIST IMPACT

1.1 Introduction

Studies of actual ship collisions with bridge piers have shown that the side and approach piers are at least as likely to be hit as are the main piers and that such collisions may be catastrophic -- in disruption of traffic, damage to the ship, and loss of life [1]. Providing adequate protection against collision may be practicable for main piers but will often be impracticable or uneconomical for these approach and side piers. Even for protected piers, the protection may not be able to fully absorb all the energy of a maximum collision and remnant forces may be delivered to the pier. Further, while it will generally prove impracticable to design a bridge pier to withstand by itself the maximum ship collision forces, which as shown in the paper by Brink-Kjaer, Broderson, and Hasle Nielson [2], can reach values of 300 to 600 MN, a high proportion of the actual collisions will involve smaller vessels and lower impact velocities.

This paper therefore addresses the design of the bridge pier itself and the practicable means which may be taken to enhance its capacity to resist impact and to minimize the consequences of ship collision.

Mr. Sven Fjeld in his introductory lecture [3] discusses indirect design measures "to obtain reasonably ductile and robust structures." In a particularly relevant section of that paper he states: "Measures to obtain ductility are:

- Connections of primary members to develop a strength in excess of the member.
- Redundancy in the structure so that alternative load distribution may be developed.
- Avoid dependence on energy absorption in slender struts with non-ductile post-buckling behavior.
- Avoid pronounced weak sections and abrupt change in strength or stiffness.
- Avoid, as far as possible, dependence on energy absorption in members acting mainly in bending.
- Utilize non-brittle members.

1.2 Ship Interaction with Bridge Piers

As has been printed out by numerous authors, the energy of the ship plus its associated hydrodynamic mass must be absorbed by such vessel-related phenomena as crushing of the ship hull and hydrodynamic damping, by elasto-plastic and crushing deformations in any protective systems, and by deformation of the pier system itself. It is this last item which will be specifically addressed in this paper since most published literature treats the pier system as a rigid structure.

In actual cases of catastrophic collision involving large ships, the ship is finally brought to rest by the deformation of the pier system, e.g., the pier is displaced laterally and crushed. In less catastrophic cases the pier has been damaged locally and displaced on its foundation but without collapse. These two illustrations show that the bridge pier system does play an important even if undesired role in the absorption of remnant energy (the $\Delta_3 E$ of Woisin as quoted by Saul and Svensson [1]).

The pier system typically consists of the pier shafts and cap, supported on a large footing which may incorporate piles, plus the soil and water acting with the pier as it is accelerated by the colliding force and then brought to rest.

It is important to note that there is an added mass effect of both the surrounding water and the soil. The forces developed are resisted not only by the inertial forces involved and the deformations in the pier proper but by the soil under the footing, that around any piles, and that acting against the side of the pier in passive resistance. Soil resistances require measurable strains in order to mobilize resisting forces.

This then becomes a dynamic mode of resisting the collision forces that reach the pier, in which the natural period of the pier-foundation system determines the degree of compliance. Fortunately the duration of ship impact by large vessels, 2 to 5 seconds or more (see Brink-Kjaer, Broderson, Nielsen [2]) is of the same order as that of the bridge pier, typically 2 to 4 seconds under maximum strain. The exact interaction depends to a high degree on the foundation soils and to a lesser degree on the relative masses of the colliding ship and pier system.

So far, the discussion has assumed a massive pier under an impact from a large colliding ship that will excite the entire pier, e.g., an impact applied at the pier base or footing. If the impact is on the pier shafts, then of course these respond primarily as a member in flexure and shear and the resistance of the pier-soil system cannot be fully mobilized.

An impact produces not only lateral shear forces on the pier but also overturning moments, leading to high bearing on the far side and reduced bearing or even producing uplift on the near side. The moment developed is of course dependent on the elevation of impact. Of importance for both gravity-base bridge piers and gravity-based offshore structures is the reduced effective bearing area which arises under high lateral forces.

1.3 Enhancing the Global Resistance of the Pier

In addition to the normal energy considerations for ship-bridge pier collision, momentum aspects are also involved, since this is a dynamic response. The larger the mass of the pier, the longer the period; hence, the greater the compliance available, especially for the more severe collisions. Thus arises our intuitive belief that a large massive pier, whether founded on piles or on soil or rock, will be more effective in resisting a collision than a pier of minimal mass.

The pier is accelerated by the collision, then decelerated by the soil. This is almost never an elastic response, thus most of the stored energy is used up in damping, although the pier will typically rebound a short distance from its maximum deformation.

The more massive and presumably larger pier will therefore mobilize greater inertial forces in itself, the surrounding water, and the supporting soil.

The mass of a pier therefore should not be minimized in design. Thick footing blocks are more desirable than thin ones.

Especially for a side pier where navigational and hydraulic characteristics may not be so severe, the pier base may be carried upward either in concrete or by simply piling a mass of gravel on top of it, contained by walls.

Alternatively the pier base may be flared up into the shaft, in a gradual transition rather than the typical abrupt change. This will then have the advantage of avoiding an abrupt change in stiffness, as recommended by Fjeld. It will add mass to the pier. It can be designed to serve as a deflector to cause the ship's bow to shear off prior to hitting the pier shaft.

In any event, to the maximum extent possible, the dimensions and profile of the pier base and base-shaft transition should be such as to force the bulbous bow typical of larger ships even at light draft to engage the base before the upper flared bow hits the shaft. This may encourage the raising of the footing block and enlargement of the base in plan, all of which also adds resisting capability.

1.4 Piling

It is increasingly common to design bridge piers using tubular (cylinder) piles of either steel or concrete capped at the waterline with the footing block. Such piers are well-suited to seismic areas because of their flexibility, but this unfortunately may reduce their capacity to absorb maximum collision impact.

These tubular piles, while flexible, tend to have a non-ductile mode of ultimate failure due to compression and buckling. The compressive capacity and ultimate curvature of concrete piles can be significantly increased by increasing the hoop (confining) reinforcement. The buckling capacity and local deformation capacity of steel cylinder piles can be significantly improved by filling them with sand.

Tension ties should be provided between the pile and capping block to prevent pull-out under overturning. If any batter (raker) piles are used, adequate reinforcement must be provided in the capping block to prevent punching shear.

Finally the mass of the footing block can be increased as noted earlier, either by concrete or gravel fill.

1.5 Scour

Scour around bridge piers can significantly reduce their capacity for lateral loads such as collision. It removes the favorable passive resistance of surrounding soil and decreases the added mass of the soil participating in the dynamic response of the pier. In the case of pile-supported piers, it may lead to unacceptable displacements at the head of the shafts. Paradoxically, within the piles' capacities, it may increase the dynamic energy that is absorbed by the pier.

This, therefore, is an added reason for taking pains to provide adequate scour protection around bridge piers in a waterway.

1.6 Keying and Doweling

Piers founded on rock, hardpan, or conglomerate may have their lateral resistance significantly increased by appropriate keying. This mobilizes additional soil mass in both passive resistance and inertial resistance. The concrete key should be checked to ensure that its shear capacity is adequate.

The overturning resistance as well as the shear resistance can be increased by doweling from the pier base into the rock.

1.7 Pier Shafts

If these are impacted, as by a large barge or flared bow of a ship, they have comparatively little resisting capability. As they deform in flexure, failure in compression and shear will usually occur before the global resistance of the pier can be mobilized.

Many dual shaft piers are connected either at the top by a pier cap and sometimes by intermediate diaphragms as well, causing the two shafts to act as a rigid frame. In this case, the far shaft may fail in compression and the near shaft in tension. In the case of the Tampa Bay Bridge, the near pier failed by pull-out bond failure of the lapped splices of the vertical bars. The far pier failed in compression in a brittle fracture mode.

The ultimate capacity of these shafts can be enhanced significantly at relatively small cost.

- Lapped splices should be staggered and employ double the code length for overlap, since the code requirements are for static, not dynamic loads. In particular, the typical design in which all the main vertical bars from the pier base end one meter or so above the base, to lap with similar bars from the shaft, should be avoided. This is a point of maximum moment and shear, and splices should be staggered as far above the pier base as practicable.

As an alternative, mechanical splices, certified to develop full strength of the bars under impact load, can be employed.

- To prevent initiating compression failure due to high bearing under the ends of bars, laps should be tied at both ends.
- Compressive failure, combined with bending can be rendered much more ductile by means of confinement. Tests on rectangular cross-section members have shown that the ultimate curvature (while still carrying the design axial load) can be increased by a factor of three (to a strain of 0.008) by providing proper confining spirals or stirrups, in an amount similar to that required for seismic design of columns.

  Tails of stirrups should be turned in and anchored in compressive zone.
- Increasing the vertical steel reinforcement, especially near the juncture with the base and cap, can significantly improve ductility as well at ultimate moment capacity, especially if combined with increased confinement.
- Punching shear capacity of hollow shafts can be improved significantly by the use of through-wall stirrups, as described for the shaft walls of offshore structures by Fjeld. [3]

In some cases, twin shaft piers can be designed so that even with the rupture of one shaft, the cap is so connected to the remaining shaft that it can carry the dead load of the span in cantilever. This provision has also been mentioned by Fjeld. [3]

1.5 Superstructure Considerations

In a number of catastrophic ship-bridge collisions, the dislocation and deformation of the pier and the shaft have caused a span to fall off its bearings. This is analogous to the similar problem experienced so often in earthquakes.

Longer bearing (support) areas can be provided.

Stops can be provided at the ends of cap girders, to prevent girders falling off sideways.

Restrainer devices, similar to those used in Japan and California, should be provided to connect superstructure elements on all overwater spans.

Finally, chains have been installed which catch a span or girder even after it has moved off the support, preventing it from falling free.

This type of failure, so catastrophic is consequences, seems inexcusable in the future, since preventive action such as noted above, is so economically and easily accomplished.

Finally, although bridge authorities have been slow to adopt it, the need is being recognized to incorporate signal lights and warning devices at the ends of bridges to stop the senseless loss of life due to roadway traffic continuing to drive over the open span.

2. CONCLUSIONS

The ability of bridge piers to absorb ship collision without catastrophic collapse can be significantly enhanced by selecting appropriate configurations for the pier base.

The evaluation of the energy dissipation during collision should consider the dynamic response of the bridge pier-foundation system. The ability to exhibit "compliance" depends on the period of response of the pier foundation system under large impact forces relative to the duration of impact. For this reason, massive piers have greater energy absorbing capacity under major impact.

The capacity of pier shafts to absorb impact and their ductility can be increased by up to three times by increased splice and anchorage embedment lengths, and by increased confinement in the form of properly detailed hoop steel. Similarly, the catastrophic dislodgement of superstructure girders and spans can be inhibited by enlarged bearing support areas, and restraining devices.

Structural solutions, such as those outlined above, cannot by themselves give full protection but can, at minimal increase in cost, enhance the ductility of the overall pier system and minimize the consequences resultant from ship collision.

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