Henderson Colloquium 2004

Designing for impact loads specified in different ways.

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As a bridge designer I find that an increasing proportion of design time is spent addressing issues related to hazards - either avoiding them or protecting against them. In the case of ship impact, avoidance means designing longer spans, and protection means designing piers capable of resisting very large horizontal forces. This emphasis on hazards comes from the recognition that a bridge is part of an economic system delivering reliable transport, and its reliability is a major part of the economic value of a transport system.

The Oresund Bridge project demonstrated these points (Figure 1). The rational minded client - a joint Danish/Swedish government body called Oresundskonsortiet - specified the required operational reliability in terms of the probabilities that the bridge would not be operational, due to any cause, for a day and for three months. As designers we were not used to such a high level design specification. When designing the foundations it was necessary to know if money spent on improving their resistance to ship impact would give more or less improvement to the operational reliability than if it were spent on intumescent paint for the steel superstructure.

Figure 1: Oresund Bridge

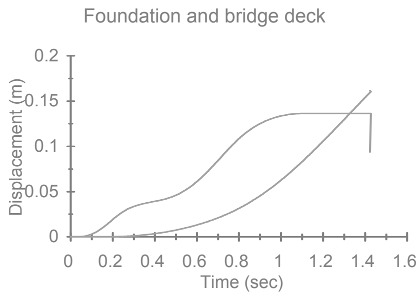

Figure 2: Displacement / time plot for Oresund Pier under ship impact

On a big project like Oresund it is cost effective to analyse the ship/pier interaction in some detail, with a non-linear transient dynamic analysis which takes account of the characteristics of the crumpling of the ship's bow, and the soil/structure interaction (Figure 2). As an aside, because the problem is basically one-dimensional, much of the analysis can be undertaken with a spreadsheet.

We have to resist many other and lesser dynamic loads and most of them are specified as static forces. It is safe to specify a dynamic impact as a static force with a value at or near its peak instantaneous value, but it may be very uneconomic. An impact is resisted by the strength of the resisting structure, but it is also resisted by the mass of the structure. If the impact is specified as an equivalent static force the designer has no way to invoke the benefit of the mass. In many instances it may be cheaper for the structure to resist the impact with mass rather than strength but, if the impact is specified statically, this opportunity is lost.

This paper is a discussion of the issues. It is part of a work in progress. There are two questions to explore:
1. Are there design opportunities with significant economic benefits which are being missed?
2. Is there a simple analysis which can be used to account for mass in impact resistance?

The dynamic behaviour can be visualised in two completely different ways. The first visualisation is the simpler one to describe. It is used in non-linear analyses. The analysis is sliced into very small time steps. The masses in the system are ascribed velocities as well as displacements. Forces on a node which are not resisted by the forces in the elements connected to the node result in an increase in velocity. This is a direct expression of impact being resisted by mass. Some of the applied force is resisted by the D'Alembert forces, the sum of the mass*acceleration reactions from each mass node. The method is so effective in analysing general structures that it is often used to solve static as well as dynamic problems, when it is called dynamic relaxation.

Using this model it is clear that if a short impulse is applied to a flexible structure the initial resistance is all due to the mass - there are no element resistances until some deflection has occurred - and the impulse is over before the rest of the structure has felt the force.

The second visualisation is the linear modal one. When the duration of the impulse is very short compared to the period of a mode, the peak internal forces in the resisting structure away from the impact are much less than the peak impulse. Figure 3 shows the structural response against duration/period. This also shows the dynamic overshoot which comes from a sudden load. If the duration of a square pulse is greater than 16% of the period - it is probably more instructive to visualise 64% of a quarter period - the force experienced by the member is greater than the peak applied force.

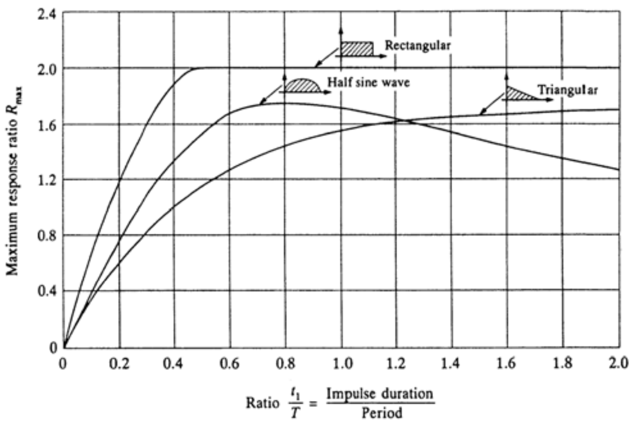

Figure 3: Structural response / duration plot

This method only gives clear insights for a structure which approximates to a single degree of freedom, such as a stiff deck plate on flexible columns under a horizontal deck impact. The reference frequency Fref is a property of an applied impulse. It is the frequency of the single degree of freedom structure which results in a peak response in the structure which is equal to the static response under the peak force in the impulse. For low frequency structures the response factor is approximately F/Fref.

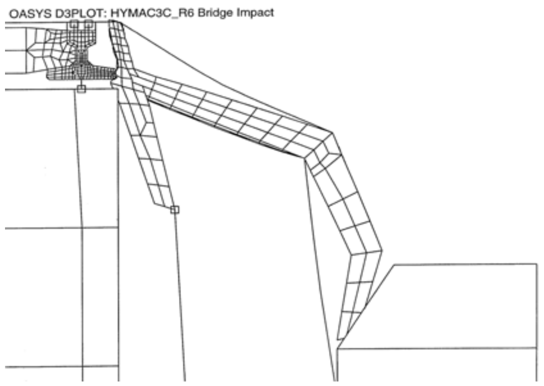

Figure 4: Analysis model of excavator

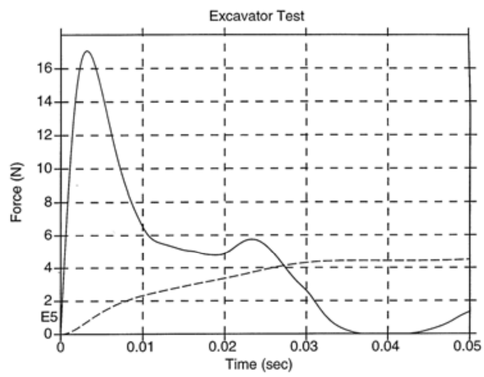

Figure 5: Force / time plot for excavator impact

The table below records approximate data for four different design situations. The data for 1 and 2 come from full scale tests performed at MIRA, and simulated by Arup for the Highways Agency. Figure 4 shows the configuration of the analysis model of the excavator arm hitting the bridge deck. Figure 5 shows the force/time plots from the full-scale test and the analysis. In the table the comment "promising" indicates that the high value of Fref is likely to be much higher than the main modes of a bridge deck, but not the higher harmonics.

The data for 3 and 4 come from the design of the Oresund Bridge. Figure 6 shows the modes of the towers. The design brief included an impact description of a commercial airliner hitting the tower. The description seemed to match the characteristics of a Fokker 100. The design benefited from having no crossbeams between the towers because the frequency of the tower was so low. Figure 2 shows a displacement time plot of a main pier under ship impact. The brief allowed the pier to suffer a permanent horizontal displacement of up to 100mm, provided this was taken into account in the design of the remainder of the bridge. The lateral deflection of the deck under the ship impact is also shown. Because the time of the impact is short compared with the period of the deck, the effect is similar to a step function displacement.

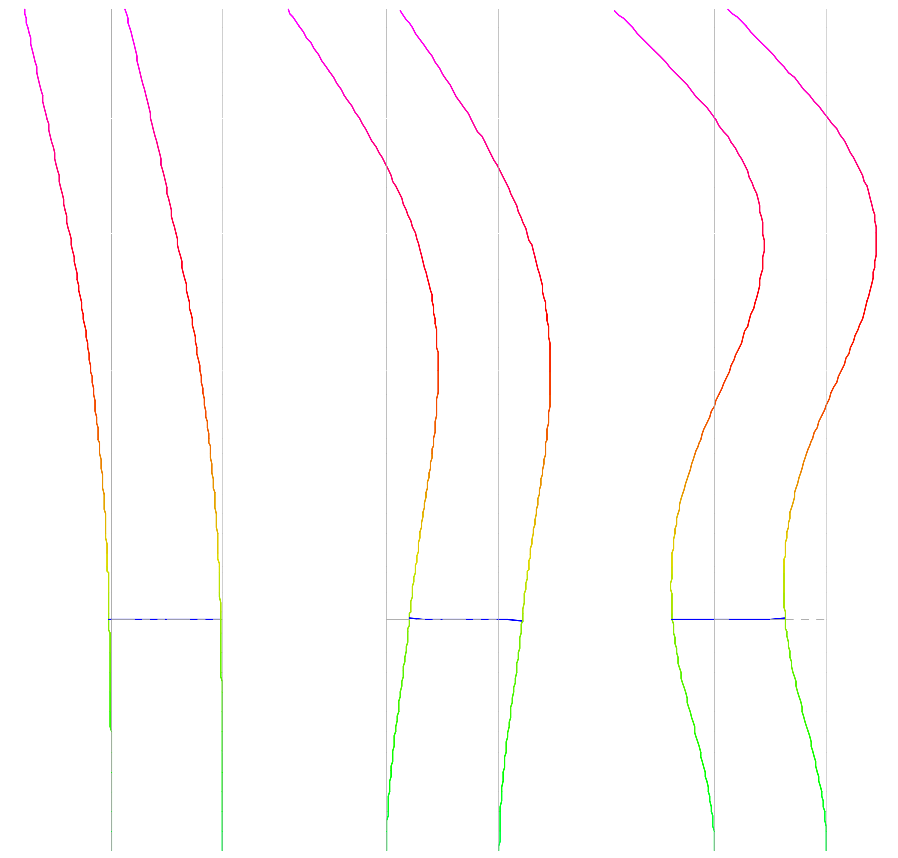

Figure 6: Modes of the Oresund bridge towers

	Velocity	Peak force	Duration	Shape	Fref	F	
	m/s	MN	ms		Hz	Hz	
1. Excavator arm on deck.	18	1.7	10	sine	27		promising
2. HGV on column	18	5.6	120	sine	2.3		
3. Aircraft on tower	130	40	230	sine	1.2	0.22	promising
Ship impact	10	200	700	sine	0.4		
4a Deck motion						0.24	promising
4b Pier motion						>1	

A designer can only invoke the benefits of transient dynamic analysis, or pseudo dynamic analysis (e.g. F/Fref) if the impact is described with data on durations as well as force. Please could equivalent static loads in design rules be described with the additional information of a half sine wave duration, t1, whose use is optional.

For example, the impact in Figure 5 can be described as a half sine wave with $t_1 = 9$ ms, and Pmax = 1700 kN. From Figure 3, the Fref condition applies when $t_1/T = 0.26$, so Fref = 0.26/0.009 = 29 Hz. It is unlikely that the bridge deck will be stiffer than one with a frequency of, say, 8.6 Hz. So the impact in Figure 5 could be described as an equivalent static force of 500 kN with a half sine duration $t_1 = 30$ ms. This is the current equivalent static impact force in BD 60/04. If the standard gave this value of t_1 it would be possible to derive Fref as 0.26/0.030 = 8.6 Hz. Hence, if the designer knew the frequency F, they could design for a static force P = 500*F/8.6 kN. Some guidance would be needed for the selection of F, because all structures are multi-modal.

Figure 6 is a useful picture to discuss a common bridge situation. A line-like structure is struck at a random position. If the tower were struck at the top it is intuitive (why?) that the behaviour would be dominated by the first mode, and an SDOF approach would be valid. With the impact at an intermediate level a different approach is required. The concept of apparent mass is useful. If a line-like structure is excited with a particular frequency it will respond as if it were a point mass. This apparent mass is a function of frequency. The impact force can be converted with a Laplace Transformation into a frequency spectrum. With a plot of apparent masses against frequency and position, and with the impact spectrum, it might be possible to judge the position of impact which would give the greatest response.

A current project is the Drachten Cycle bridge in The Netherlands (Figure 7). The Dutch rules require the deck to be designed for a 2 MN force from an over-height lorry. This is a very severe load. From the MIRA tests it is likely that the duration of impact would be very small. We intended to use this to argue down the effective forces to be carried, in particular, in the bearings between the deck and the abutments. Because the impact can occur within about 5m of the abutment it is the higher harmonics which will be relevant. Rather than undertake a transient dynamic analysis of this situation, we have chosen to accommodate the specified forces as static loads. By making the abutments semi integral (the Dutch are not used to integral bridges) we are able to use pin bearings which we believe will be rugged enough to resist the mixed forces, including uplifts, which arise from the impact.

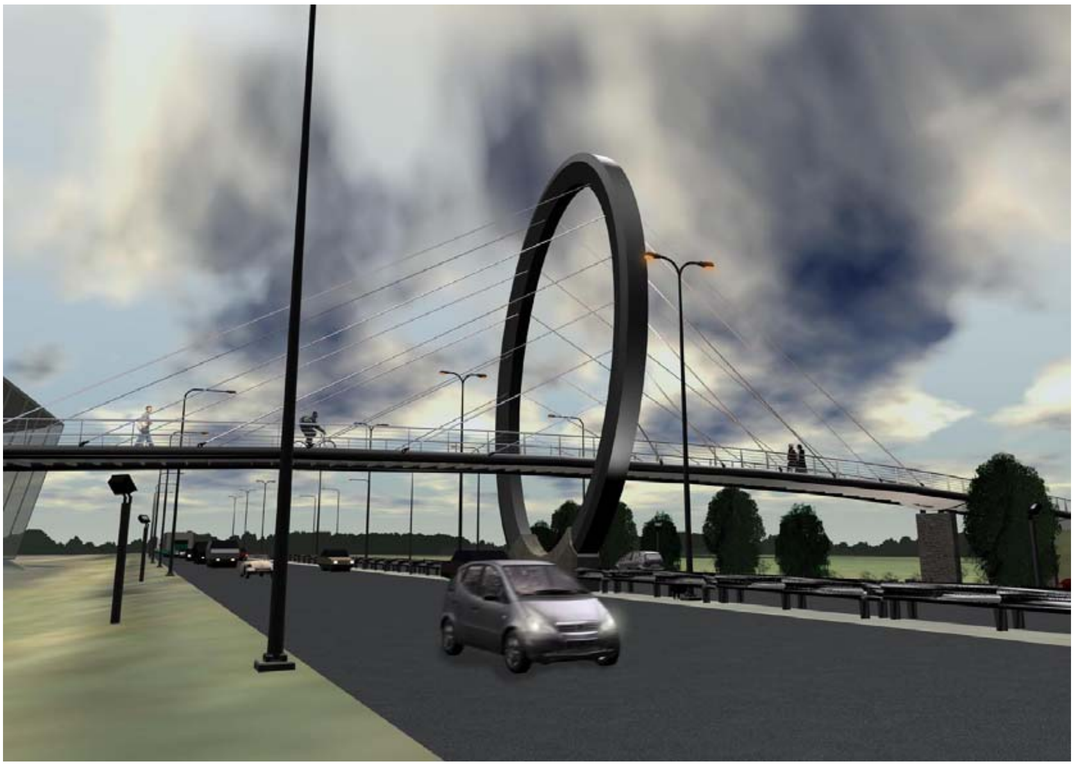

Figure 7: Drachten Bridge, The Netherlands.

In answer to my two questions, on a subjective basis from my recent experience:

1. The opportunities for design economies are not a great as might be expected from a simplistic look at Figure 3, but there are cases which would benefit.
2. The crude but simple application of F/Fref will provide the benefits.