HENDERSON COLLOQUIUM 2004

Designing for the Consequences of Hazards

Brief: 'To be focussed on specifically structural aspects of how design requirements are defined, in order to achieve the best outcome'.

HAZARDS IN THE LEISURE INDUSTRY ***A P Mann Babtie Group***

Introduction

It seems to me there are two broad divisions within the Leisure Industry. Firstly there are those projects for which large crowds dominate and stadia naturally come under this heading. Secondly there is the division in which hazards to individuals predominate and the structures we build in theme parks fall within this group. Clearly the hazards in both groups relate directly to human life; in both cases very large numbers of people are involved and in both cases, any accidents tend to make headline news. In both cases the forces involved for structural design are imprecise and in both cases the criteria we set for acceptance are fuzzy and require some judgement.

If there is an accident on a ride, there is an immediate loss of income; the whole revenue stream dries up. Beyond that, there may be a serious loss of confidence in the park itself, so the financial penalties might be severe. Hence achieving ride reliability is always a design objective but what is 'best outcome' is open to debate

Stadia

There are a number of accident possibilities in stadia and lessons from the Bradford Fire, Hillsborough and other events have led to the publication of guidance such as 'Safety in Sports Grounds'. Of direct importance to structural engineers is the issue of crowd loading and the possibility of either accidental or deliberate excitation of structures by mass crowd movement. This topic has been known about intuitively for a long time (anecdotes about soldiers needing to break step over bridges etc). But we have in recent years had failures of temporary grandstands and some well publicised problems in newly built stadia such as the vibration of the Cardiff stand in a pop concert. Cumulatively this has led to the publication of 'Interim Guidance' from the Institution of Structural Engineers but this is not yet satisfactory.

The Guidance offers some structural frequency limits that should be achieved if possible. But thereafter, if these limits cannot be met, the further advice is to progress via dynamic analysis to assess accelerations, although this is accompanied by warnings that the subject is very imprecise. In terms of commercial construction, when one has to gain acceptance off an authorising body, this is a high risk design strategy.

We have recently completed the dynamic design work for a new stadium implementing the Interim Guidance, a process that has thrown up a number of difficulties. These may be summarised as follows:

It's very difficult to achieve the target threshold frequency levels. In practice, we may be faced with offering a client the choice between a structure that has the right frequencies but is so braced up its functionality is very poor.

(1) Frequency is a poor criterion for judging acceptance. More than that, it's a very expensive criterion. Given that $f \propto \sqrt{(\text{stiffness} / \text{mass})}$, it takes a huge shift in stiffness to effect a marginal increase in frequency and of course any increase in mass is in part self defeating. Thus trying to design to frequency limits can be very costly.

(2) In some cases, the criterion cannot be met. In normal static structural engineering, given a sensible span and load, it's not too difficult to design a beam with the right safety factor. By contrast in dynamic loading cases, the frequency is so heavily dependant on the span that given a longish span the engineer may have an impossible job of getting a beam to suit a desired frequency. It's just not that simple. In these designs, an acceptable structural solution is a compromise between structural layout (critical for sight lines etc), cost and acceptable performance. And 'acceptable performance' means achieving safety but perhaps compromising on serviceability.

(3) The design of a balcony serves to illustrate the need to account for human perception. By reference to Figure 1, if the frequency is below say 6Hz, peak accelerations due to crowd activity would be experienced by a spectator sitting at the balcony front in the middle of the precast seating units. The natural frequency and the accelerations at this point are a function of the steel and concrete member stiffnesses and of their masses. To achieve a large acceleration, the balcony has to be excited either accidentally or deliberately by rhythmic movement. The mass of the crowd has to be reasonable high in relation to the mass of the structure since clearly a flea jumping up and down for infinity at the balcony frequency (resonance) is still not going to produce any measurable displacement. Assuming the crowd mass is sufficient, a fairly bad case exists for a balcony with frequency about 4.6 Hz, which is stiff but below the Guidance 6Hz target. If crowds jump up and down at about 2.3 Hz which is just about the maximum rate they can manage in coordinated fashion, they can excite the balcony at the second harmonic (2 x 2.3Hz). But for this to be a real problem, a number of variables have to coincide:

- Only a person sitting is affected, so someone has to be sitting in the worst place (front row middle)
- The crowd who are jumping have to be high enough in mass in relation to balcony mass.
- Crowds have to jump in harmony at the right peak frequency for long enough periods. Their ability to jump in a co-ordinated manner decreases as the frequency increases. I.e. it's quite easy to move in rhythm at 1 Hz but really hard at 2.3 Hz. It's even harder to sustain that co ordination for more than a few cycles. (Figure 2)
- To get the worst response, crowd have to jump. If they 'bounce' the input energy is less and so is the response.

Thus the acceptance criterion is fuzzy. But get it wrong and there may be very serious consequences to either safety or serviceability. Try to be conservative, and it's extremely expensive and the end product may be a poorly functional stadium. The Institution is putting in effort to promote better understanding in this area.

Theme Parks

We are concerned here with individual rides and with the hazards that affect their design. Rather surprisingly there is quite a lot in common between ride design and hazardous industries such as the nuclear industry so 'learning from each other' is certainly possible and beneficial.

A ride is a 'system', that is it's a collection of civil, structural, mechanical and electrical systems all interacting and mutually controlled. The control system normally utilises a plc and the programming of the control system and the design of the ride configuration requires a Risk Assessment. There is a direct link between the Risk Assessment and the arrangement of the ride and the hardware supplied for the control system. It's perhaps easiest to envisage this by looking at a roller coaster.

The loads a coaster applies to a track and thence to its structural supports are dynamic. They can be calculated with relative accuracy and indeed they must be known since a key piece of data is the vehicle speed at any point on that track and the dynamic loadings are related to that speed. Broadly we have loadings in the range $-0.5g < \text{Load} < 4g$ at any point. There are of course complications in that the forces we're interested in act in the three orthogonal directions at any one time. Furthermore, at any section of track they vary depending on which part of the train is applying them (i.e. they differ between the front, middle and back of the train). Figure 3 shows a record of accelerations as measured around a typical track and they comply quite accurately with design predictions.

The accelerations and corresponding forces directly influence the commonest structural problem, which is that of fatigue. In standard road bridges, fatigue is an issue but not an overwhelming one. In roller coaster track, the reverse is true and there is uncertainty with potential for accidents. On a bridge, the ratio 'vehicle to structure self weight' is low and loads are generated simply by gravity (1g). In a coaster, the car to structural weight ratio is high and the force at any points may be due to 4g. Moreover there are multiple wheels on a coaster and the track is thus subjected to a large number of high load cycles. What makes the stress cycling uncertain is the influence of impact and how this might be generated either by imperfect dynamic design (say as a car bulldozes its way between the constraints) or from such features as track misalignment. Figure 4 shows the results of wheels driving over a step in the CHS running surface. Every time the wheel goes over, it thumps down on the track in front and eventually the tube starts to split in the longitudinal direction. It's also common to generate cracking at the supports to the CHS running track i.e. where there are stress concentrations.

A more invidious form of fatigue is not uncommon. In structures supporting moving plant, the number of cycles of operation is normally considered a key factor in determining whether fatigue exists or not. But that is only partially true. There are two kinds of fatigue: low stress / high cycle and high stress / low cycle of which the latter might be better thought of as 'alternating plasticity. In one such case, cracks in a seat arose because of small imposed displacement. The nominal stresses were trivial. But the crack came about because on every cycle of load the seat hit a stop and the bend at the back (junction seat to upright) was forced momentarily up to yield. There was no manifest distortion because the load was strain controlled. But effectively, the steel at the bend was taken on a cycle of high stress loading for just a few hundred cycles and then cracked badly (Figure 5 shows another seat crack example). The lesson is to be aware of high strain controlled effects generated by some imperfection (we have seen the same strain controlled stress effects in certain crane structures). The second lesson is that in any system subject to fatigue where crack progression can potentially have serious consequences, the total protection philosophy must include maintenance and regular inspection and an inspection regime that includes knowing where to look. In turn that means designing for 'inspectability'. Severe accidents have occurred because of fatigue cracks progressing undetected below seat coverings.

Any ride is a combination of mechanical / electrical items and a control system. To assess potential hazards / accidents it is necessary to thoroughly understand the system and assess what might happen should any part of that system fail. It has to be understood that in mechanical and electrical engineering components are expected to fail and require replacement. The procedural process for investigating this might be a *Risk Assessment* or a *HAZOP*. The outcome of the procedure should be a clear understanding of the consequences and an indication of what to do to mitigate the potential harm. Harm might be 'loss of life or injury' or it might mean excessive loss of income. We always need to distinguish between commercial and non commercial consequences. Possible structural mitigation measures could be the need for more secure passenger containment; the need for redundancy in the support structures or the need for inspection. Figure 6 shows anti roll back devices installed having foreseen the potential accident of a train slipping backwards downhill. Indirectly, there may be a need to design the control system so as to minimise the risk of the accident occurring, for example, the risk of two trains colliding or the risk of generating excess force by cars travelling too quickly. The latter for example, may be controlled by sensor speed detection and a logical response such as to activate 'trim' brakes and 'slow the cars'.

Since cars are regularly sent around the track, the control system ought to 'know' that the outward journey is nullified by a car arriving back in the station. Obviously if one car is stuck on the track somewhere and a second is despatched, there is a collision hazard. It is possible to check this via the control system. This is no different to the 'blocking' system adopted on railways. As we all know, the consequences of a vehicle crash spread far beyond the immediate costs of repair. Hence in ride design there is a real incentive to design 'reliably' to avoid severe financial penalties. But for other potential accidents like fatigue failure, some balance is drawn between, initial avoidance on the one hand and ride life and detection and repair on the other

Generally the process of examining potential faults within a controlled system, and then determining how to eliminate them or minimise the consequences within financial constraints is the same discipline as used on high hazard chemical plant or the rail system. It may be complemented by numerical probabilistic studies, though that is not normal in the leisure industry. Collectively it is these procedures that underpin any Safety Case.

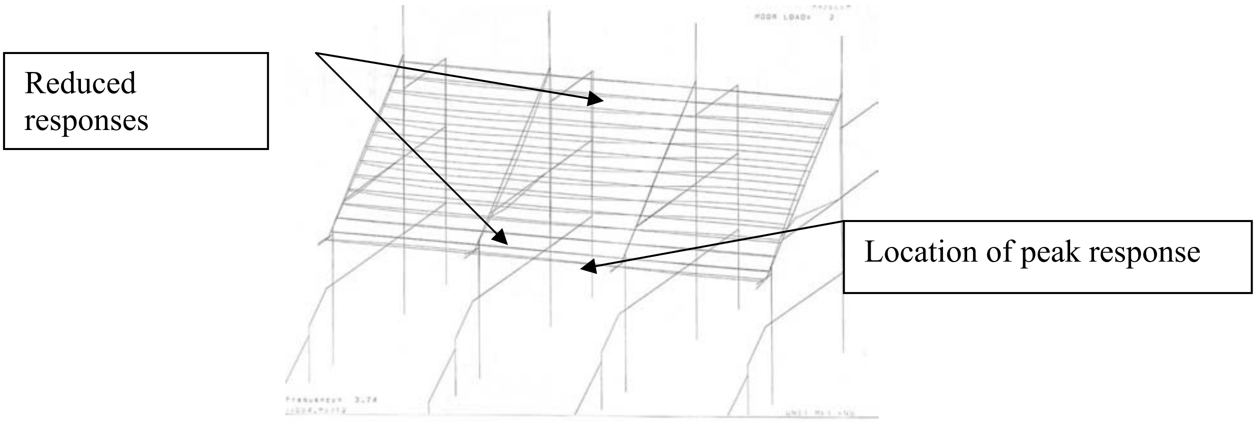

Figure 1. Grandstand Frequencies

Figure 2. 'Synchronised jumping'

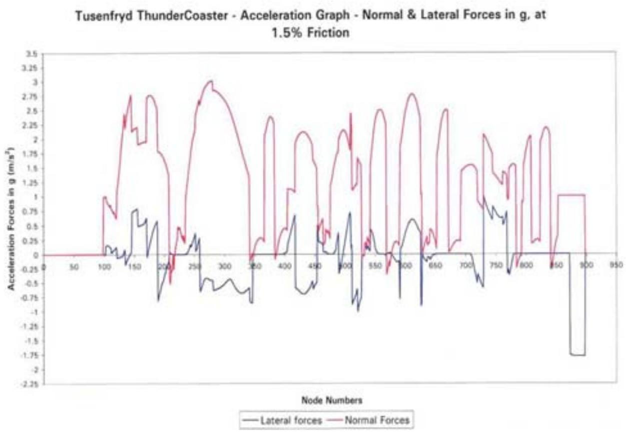

Figure 3. Record of accelerations around a coaster track

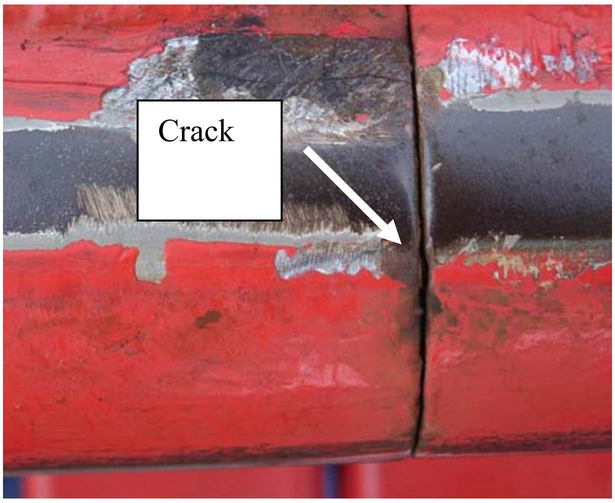

Figure 4. Fatigue crack in running tube.

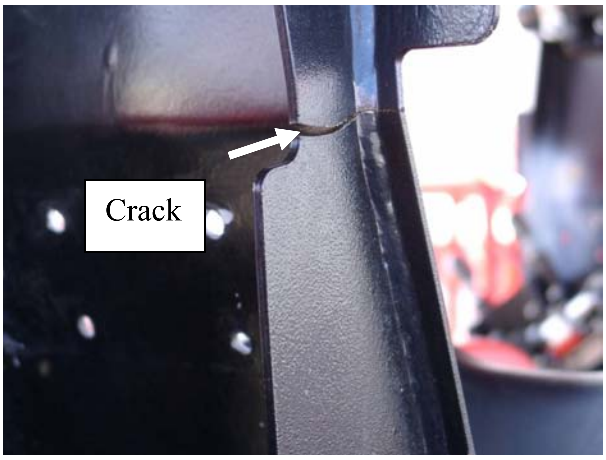

Figure 5. Fatigue crack in seat

Figure 6. Anti roll-back devices.