Adding confidence and reducing risk - the role of independent design checking in major projects

Ian FIRTH
Partner
Flint & Neill
London, UK

Ian Firth graduated from the University of Bristol and joined Flint & Neill in 1979 becoming a Partner in 1990. He obtained a Master's Degree in Structural Steel Design from London's Imperial College in 1982, and has recently been elected a Fellow of the Royal Academy of Engineering. He is mostly engaged in bridge projects and is known for his work both as designer and as checker.

Summary

Responsible clients and designers commission an independent check of their designs, particularly when the scale or complexity of the project requires it. This paper explores the culture of independent checking that exists in the UK, especially in connection with major bridges, and examines the benefits to be gained from such an approach. The cost of adding confidence and reducing risk through such a check is very small compared to the enormous benefits gained, particularly on major projects.

The author draws on his own experience as well as published information to illustrate the importance of establishing such a culture of independent checking everywhere.

Keywords: Independent design check. Design verification. Independent certification. Category 3 checking. Design review. Risk reduction.

1. Introduction

Following the collapse of the steel box girders bridges in Milford Haven (Fig.1) and Melbourne in 1970 and the very significant work carried out by the Merrison Committee of Inquiry in preparing new design and workmanship rules for such structures, there has been a culture of independent design checking for major bridges in the UK. [1] Similar practices previously existed for checking dams and nuclear installations, but none as rigorous as was now proposed for major bridges.

Fig. 1 *Milford Haven Bridge, Wales, following the collapse*

What started as a need for checking of steel box girders soon spread to encompass all major bridges and those of unusual or complex behaviour. No major bridge is now constructed in the UK without such an independent check being carried out first, and the same is true of any strengthening or major repairs to such bridges. In the case of so-called Category 3 structures, the check is carried out by consultants acting independently of the designers using completely independent analysis modelling and methodology but working to a common set of design criteria. At the end, both the designer and the checker have to certify that the design meets those criteria.

There is no doubt that such a check adds considerable value and security for a client for a tiny fraction of the construction cost. As a result, this culture of checking which is already routine for bridges in the UK is now increasingly being applied to major public buildings and other structures as well. However, it is still not universal, even in major public assembly buildings where the consequences of failure would be unthinkable.

This paper addresses the essential need to develop a natural culture of design checking in all parts of the world, not just for major bridges but also other significant structures, particularly in the light of the increasingly litigious society in which engineers and designers now have to operate.

2. The need for a checker

Engineers are only human - we all make mistakes! History sadly shows how easily mistakes can and do happen and we would be very foolish if we assumed that our work was always correct and never needed checking. Civil and structural engineers carry a substantial responsibility for public safety, so we have a professional duty to do whatever we reasonably can to ensure that public safety is not compromised by anything we do. Responsible and appropriate levels of checking are therefore to be expected of us.

Safety may be our main concern but it is not the only one. We also have a duty to our clients to ensure as far as reasonably practicable that mistakes do not occur which could cost them extra time or money or which might cause some other kind of nuisance. An independent check is the most effective way of finding and correcting such mistakes.

Different levels and types of checking will be appropriate for different circumstances, but all start from the premise that two minds are always better than one. At one end of the scale there is the full numerical check, carried out by an expert engineer acting independently of the designer, to analyse the structural behaviour, check the design against detailed design criteria, and reach an independent professional opinion as to the adequacy of the design. At the other end of the scale, the check can simply involve a colleague, not involved in the design process, who discusses the project with the designer, reviews what is being done and asks some probing questions in a spirit of helpful collaboration. This latter process of design review should be part of the normal activity of any design office, whether or not rigorous independent checking is required, and should be designed to initiate lines of investigation which can reveal errors and/or identify better ways of achieving the designer’s intent.

Such design reviews are enormously valuable but not strictly the subject of this paper. Nevertheless it is worth reflecting briefly that they have served society well for many centuries. In the UK, a law was passed following the great fire of London in 1666 (Fig.2) introducing new design rules which ultimately evolved into the modern Building Regulations. Those rules defined the need to build the external walls out of stone or masonry rather than timber, for example, in order to restrict the spread of fire. But the most important aspect of the rules was the introduction of the need for checks on the design and the building process. The rules empowered the Lord Mayor, Aldermen and Common Council of London to appoint “*one or more discreet and intelligent person or persons in the art of building to be the surveyors or supervisors to see the said rules and scantlings well and truly observed*,” and the surveyors or supervisors were required to “*take the oath upon the Holy Scriptures for the true and impartial execution of their office*.” [2] Thus was born the culture and practice of checking new building construction which is still in use today.

Fig. 2 *The great fire of London in 1666 was the trigger for rigorous building controls in England*

However, full independent design checking is different from a design review or audit in that it requires independent analysis using independently derived methodologies, not merely a review of the designer’s methods and calculations.

The process of independent checking can also be extremely positive in terms of education and training, which derives from sharing first hand experiences and opinions with other expert engineers. The best kind of designer-checker relationship is one where the designer does not need to feel defensive that the checker might find an error and the checker is not seeking to score points by looking for errors, and both parties are seeking to learn from each other to mutual benefit. When a client sees two professionals working together in this way he will feel re-assured that his best interests are being well served. This is particularly true when the project involves some innovation or complex aspect. A second opinion always adds confidence, both to the client and the designer, and the design risks and uncertainties are reduced in the process.

Finally, it is worth touching on the unfortunate fact that we operate in an increasingly litigious society in which everyone seems to be looking for someone else to blame if something goes wrong. An independent design check provides an extra layer of protection to both the client and the designer by increasing the chances of finding mistakes before they can lead to expensive and distressing legal claims. It also spreads the liability for such mistakes a little – an important subject to which I will return later.

3. The steel box girder story and the British system

On 2nd June 1970, the Milford Haven Bridge in South Wales collapsed during cantilever construction of the south approach spans. This and the collapse in Melbourne on 15th October 1970 triggered the appointment of the Merrison Committee of Inquiry who immediately set about investigating the causes of collapse. A further steel box girder collapse occurred in Koblenz in November 1971 adding further fuel to the urgent need for the investigation to reach a speedy conclusion. The Committee's report and conclusions [1] are as important today as they were then, and should be essential reading for all bridge engineers. They cover not only the design rules and methods of analysis for such structures but also the contractual procedures and programmes under which they are procured. The consequences and ramifications of these tragic bridge collapses have been far reaching, and the extremely intense period of research into the behaviour of steel plated structures carried out in the ensuing years led quickly to the adoption of new design codes and methods of analysis for such structures. The lessons fundamentally influenced the way engineers have conducted their bridge designs and assessments ever since, although sadly some of these lessons are in danger of being forgotten by a new generation of engineers caught up in the rush to save money and time in the modern bridge procurement process.

Among the most important recommendations of the Committee were several relating to procedural matters, as distinct from technical design issues. Just over a year after the Milford Haven collapse, the Committee issued their interim report, the first recommendation of which was as follows:

"*The Engineer's permanent design should be checked by an independent engineer both for the design concept and the method of analysis of stresses and a certificate furnished to this effect and for compliance with the criteria set out in Appendix A [the Interim Design and Workmanship Rules]. The independent engineer should have experience and qualifications commensurate with the magnitude and complexity of the design in question*." [1]

The importance of the Committee's recommendations was immediately appreciated by the British Government of the time, and on 31st August 1971, the Department of the Environment issued instructions to all local authorities implementing the principal recommendations with immediate effect. It is a matter of concern that the low level of technical appreciation in some government and civil service circles today, and the sometimes tortuous bureaucratic procedures they are obliged to follow, may mean that the modern response to such a situation would not be so decisive.

The principle of independent checking was immediately adopted for all steel box girder bridges all over the UK and was quickly extended to apply also to all major or complex bridge structures. Such bridges are classed as Category 3 structures under the now widely adopted UK classification system:

- **Category 0** structures are only small minor constructions and do not require formal technical approval but should nevertheless be independently checked within the design team.
- **Category 1** structures include bridges with spans less than 20m and other relatively small constructions. These require formal technical approval and an independent check of the design by an engineer who may be part of the design team.
- **Category 2** covers are all structures which do not fall into any of the other categories. Their design shall be checked by an engineer or team of engineers who must be independent of the design team but may be from within the designer's own organisation.

- **Category 3** covers complex structures requiring relatively sophisticated analysis or those with spans greater than 50m, high skew angles, high redundancy, suspension systems, steel orthotropic decks, moving bridges etc. These require an independent design check by an engineer or team of engineers who are independent of the designer's organisation. It is particularly important in this case that the checker possess the necessary expertise and experience suited to the type of structure in question.

The 20m and 50m span lengths are taken directly from the Merrison Committee's recommendations but are only intended as guidelines. Each case needs to be considered on its merits and these span limits are not to be considered as absolute.

The requirements for independent design checking are set down in the Highways Agency's Design Manual for Roads and Bridges and are contained in standard BD2/05. [2] The procedures defined therein are now common practice and have been adopted in several other parts of the world, not just in the UK. The checker's scope includes the all-important check of the effects of the proposed erection sequence, and often also a review of the durability and maintenance issues.

It is important to note that the independent checker is responsible for checking the design and not the structure, and check certificates and reports should be carefully worded to this effect. Unless the checker is given an extended brief to include full time supervision of the construction works he cannot be in a position to certify the as-built structure. This does sometimes happen when a client wishes to procure independent certification that the structure has been built in accordance with the checked design, but otherwise the certification can only be in relation to compliance of the design with an agreed set of design criteria.

In addition to proposing the independent check of the permanent works design, the Merrison Committee also recommended an independent check of the Contractor's method of erection and the design of the temporary works, and these recommendations are generally now adopted in the contract conditions for most contracts. However, some of the other procedural recommendations intended to promote good and safe practice have been either forgotten or diluted in some modern construction projects. These include, for example, the proper supervision of the works by the designer. Too often it seems that modern clients or contractors are unwilling to pay for adequate resident supervision staff on site, thus increasing the risks of serious incidents during construction.

The culture of independent checking has become well established in many parts of the world, although local practices differ, but in other countries the principle of checking is less well established. In some cases a check seems to involve little more than a quick glance at the designer's calculations by someone in the designer's office, even for very substantial structures, and sadly failures continue to occur.

Other speakers in this conference are addressing some other international practices so I will not attempt to cover the same ground here. In some countries it is common for a design review to be required by a suitably qualified or registered engineer. However, there is a limit to what can be achieved and what extra confidence can be provided through merely undertaking a cursory examination of a designer's calculations. The value of such a process as a safety check, without the rigour of a fully independent analysis and evaluation, is sometimes called into question. Examples of failed structures which were supposedly subject to independent design review demonstrate the need for a more thorough and rigorous checking system than is applied in some cases.

4. The importance of independence

It is important to emphasise the independence of the checker and to recognise the essential value that this adds to the process. The author has come across a wide variety of models for so called independent checking, but sadly not all of them can be considered to be truly independent and as a result some have little if any value.

4.1 Technical independence

This requires two suitably experienced engineers to come independently to a professional opinion through a technical process of calculation, analysis or investigation.

Not all checking is valid checking. If one engineer sets up a spreadsheet to perform a calculation and another is asked to check it by entering a new set of data, this clearly does not constitute a suitable check. If there is an error in the spreadsheet it will simply be repeated with the new data.

If a checker looks closely at the content of every cell in the spreadsheet and reviews every step of the calculation (a time consuming process in the case of large complex calculations) then an error might be detected. But then again it might not.

The best way to check if the answer given by the calculation is correct is to independently start from scratch. The checker sets up his own spreadsheet, without reference to the original, and at the end the results of the two are compared. If the answers are significantly different, experienced engineering judgement is needed to determine whether the difference is sufficient to require both parties to check their calculations for errors or repeat the process from scratch. Only by this kind of true independence can all parties have confidence that the calculations are correct, or at least sufficiently accurate to allow work to proceed.

Thankfully, most design errors do not lead to collapse, but the fact that errors escape detection in the checking process is still a cause for concern. An example serves to illustrate this point. A guyed mast is under construction. A systematic error in the designer's spreadsheet results in all the guys being delivered to site exactly 3 metres too long – not disastrous but expensive! The design had been subject to review by an independent checker, but the check was not required to be fully independent. All the checker did was to examine the spreadsheet to see if the process looked correct, but sadly the systematic error was not found. Had the checker set up his own independent spreadsheet to independently calculate the guy lengths it is very unlikely that the same systematic error would be made. One of the advantages of the true independent check is that the chances of both the designer and the checker making the same mistake are very small.

It is worthwhile pausing to reflect on the application of professional judgement which is always necessary in engineering processes. Engineering is not an exact science, and almost everything we do is associated with some kind of approximation, estimation or assumption. Thus the chances of two independent processes delivering exactly the same numeric answers are very small. This is to be expected. A checker is not trying to replicate exactly the same answers but to come to an independent professional judgment. The two independent answers to a particular calculation may only be within 10 or 15% of each other, but what matters is that the two engineers should reach the same conclusion regarding aspects such as "Is it acceptable or not?"; "Does it comply with the code or not?"; "Does it need strengthening or not?"

This principle lies behind the fundamental basis and benefit of independent checking and must not in any way be diluted if the value of the check is to be maintained. Thus, in the case of a fully independent check, it is vital that the checker carries out his own independent structural analysis, preferably using different analysis software. The approach to modelling the structure should be independent too, based only on the checker's interpretation and examination of the design drawings. This may result in two very different models but this should not matter. The important thing is the engineering judgement and interpretation of the results, not the exact replication of the designer's computer model.

The author knows of situations where a client has required the checker to use the same computer software and the same structural analysis model as the designer, and to check that their input data was exactly the same before running their supposedly "independent" analyses. The value of this exercise is questionable as it is merely a check on the ability of two people to enter data correctly into two separate computers.

It is helpful to be able to compare certain key results from two genuinely independent analyses, such as overall and individual foundation loads, maximum deflections under a given live load pattern, fundamental natural frequencies of vibration etc., but this can be done without the two models being exactly the same in every respect.

All of this pre-supposes that both the designer and the checker are suitably qualified and skilled individuals, supported as necessary by expert teams, and able to reach a professional engineering judgement confident in an opinion based on experience. In presenting the findings of the Merrison Committee and introducing the new Interim Design and Workmanship Rules in 1973, Sir Alec Merrison said that "*no amount of writing of design codes and writing of contracts can in the end be guaranteed to prevent the results of stupidity, carelessness or incompetence. But one can do a great* *deal to discourage these vices and that must be done*." [6] The need for ensuring proper competence in the designer and the checker and a suitable procedural framework under which they can be free to apply that competence is far more important than the application of mere design codes and standards. This places a significant duty on the client to ensure that he appoints a suitably qualified checker. A poorly experienced checker can de-rail the process and lead to costly errors or delays.

4.2 Commercial independence

The checker must also be reasonably free from undue commercial constraints and conflicts of interest if he is to be able to freely use his own expertise and engineering judgement to perform whatever independent technical checks are required. Otherwise, such constraints and conflicts can prevent him from reaching an independent professional opinion.

Fundamentally, the checker should be independent of the designer. Ideally this means that he should not be appointed directly by the designer but preferably by the client. (Fig.3) If the designer appoints the checker, he may try to influence the outcome of the check because under the terms of the sub-consultant appointment he will have powers to do so if he chooses.

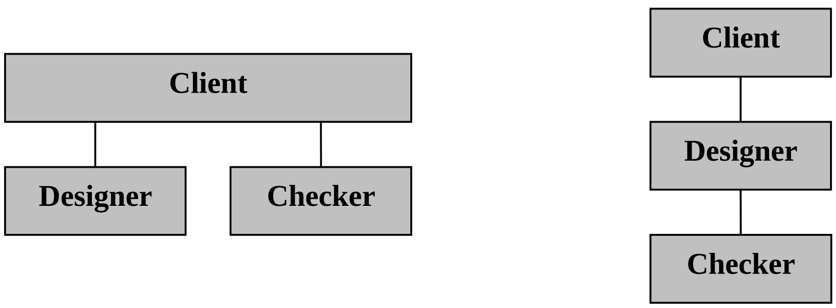


Fig. 3 *Possible designer-checker arrangements.*

Checkers can be put under enormous pressure in some circumstances to reach a conclusion which may be at odds with his professional opinion. This can happen, for example, when a contractor is already building part of the structure which is still being subject to independent design check because of inadequate time in the programme. There may be pressure on both the designer and the checker to accept the design without modification because it has already been built! This may require extra, more detailed checks or a review of the design criteria to see whether an alternative method might give better results or whether reduced safety margins could be acceptable. In such circumstances the independence of the checker from the designer becomes vitally important.

Financial pressures can apply if a checker's fees only paid once he signs a check certificate, possibly leading to a temptation to cut corners in the check because of such commercial constraints.

Under design and build contracts there are several possible checker appointment models, as discussed further below. These need to be arranged to ensure the independence of the checker.

5. Contractual arrangements

The arrangement of the design and check appointments will depend upon the procurement process for the bridge or structure in question.

5.1 Traditional procurement

Traditionally, and still in many cases today, the client or owner will commission an engineer to prepare a fully detailed design prior to inviting tenders from contractors for the construction. The client also appoints an independent design checker. If the work is properly programmed, this enables the check to be completed and the design to be certified prior to the invitation of tenders. Any uncertainties in the design can to be minimised prior to awarding the contract and the client is able to influence the design and control the design risks.

This process is recommended for a complex or strategically critical project, where there is no escape from the need to spend sufficient time and effort in the design stage to reduce design uncertainties prior to embarking on construction.

The Tsing Ma suspension bridge in Hong Kong serves to illustrate this process. (Fig.4) This was a traditional full Engineer's detailed design, carried out by Mott MacDonald and independently checked by Flint & Neill prior to inviting tenders for construction. The normal checker's role was extended to include the derivation of certain design criteria corresponding to particular areas of F&N's expertise such as wind loading, aerodynamic response, traffic loading and temperature effects. These criteria were agreed with the Client, Hong Kong Highways Department, prior to completing the design and the independent check. F&N's role was also extended to include an economic review of the design and certain other aspects. Detailed reports summarising the procedures and findings of the check were produced, and the client remained fully engaged in the process throughout, satisfying himself through the independence and rigour of the design and check processes, that his best interests were being served and design risks were satisfactorily controlled.

When the tenders for construction were received and reviewed, the successful contractor proposed a change from pre-formed parallel wire strands to aerial spinning for the construction of the main cables. This required F&N to re-check the erection procedure to check the suitability and acceptability of the necessary design changes. F&N was also retained during the construction period to provide independent advice and expertise in connection with certain inspections, tests and specification issues.

Fig. 4 *Tsing Ma Bridge, Hong Kong*

The main lessons from this example are that a well-informed client recognised the importance of a full and thorough independent design check and the need to allow enough time to do it properly in advance of construction, and also made full use of the expertise and experience available to him through both designer and checker working together in a spirit of helpful co-operation throughout.

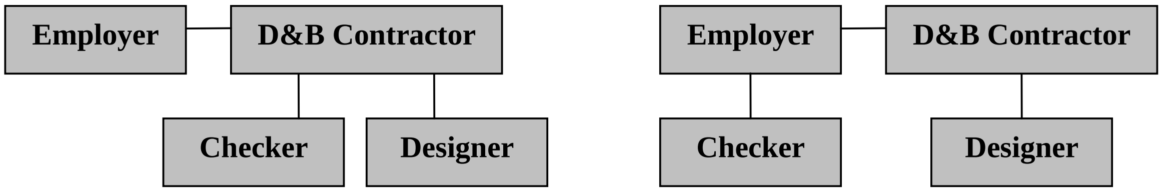
5.2 Design and Build

Today, more and more public sector projects are procured through design and build contracts, but there are several models for the appointment of the independent checker. If the structure is not Category 3 then the check can be carried out by the designer's organisation. But if a Category 3 check is required the checker must be independent and may be appointed either by the Employer or the Contractor, but preferably not by the designer for the reasons outlined above.

It is common for the Contractor to appoint both the designer and the checker, and this allows him to control both the design and check activities to suit his overall construction programme. (Fig.5a) At least with this model the Contractor cannot use delays by the Employer's checker in certifying the design as a possible excuse for a claim. However, there are two possible problems with this approach. Firstly, there is an argument that the check may not be considered to be truly independent of the design if both are strongly influenced by the Contractor's design preferences, and secondly the Contractor may apply undue pressure on the checker to conclude his check favourably without being given sufficient time to properly consider and evaluate the issues.

When the Contractor appoints both the designer and the checker, the Employer will often retain his own consultant, at least on large projects, to ensure that the correct procedures are followed and to verify that the necessary certification is provided prior to construction. Occasionally, the Employer's consultant in such a situation will query the opinion of the designer and/or the checker and seek extra assurances that the design is adequate before allowing construction to proceed.

From the point of view of the check, a better arrangement is sometimes for the Employer to appoint the checker directly to check the Contractor's design proposals. (Fig 5b) In this way, the checker is able to advise the Employer independently of the Contractor and the designer, and can also participate in the construction supervision. The Employer has direct access to the checker's expertise and experience throughout, and he has no need to appoint his own separate consultant to advise him, thereby saving on the overall cost of the project. This model was used on the Ting Kau Bridge in Hong Kong, for example.



Figs. 5a and 5b *Alternative Design & Build contract arrangements*

However, sufficient time must be allowed in the contract programme for the submission and checking of the design, usually in a series of design packages, and the Contractor is not fully in control of this programme. In this instance, the Employer is responsible, through his checker, for certifying the design independently of the certification provided by the Contractor through his designer. The contract needs to allow for the possibility of problems being encountered and some aspects of the design having to be modified, re-submitted and re-checked without causing delays which can lead to subsequent claims.

5.3 Checks by investors and others

The delivery of major infrastructure projects usually involves insurance companies, banks and other financial organisations, in addition to the client or owner and local or national authorities. This is particularly true when there is an element of private sector investment in a project, as is increasingly the case for major projects. Each of these organisations commonly needs some kind of check to safeguard their interests, in addition to the normal Category 3 check carried out by the Contractor or the Employer. Such additional checks may take the form of a due diligence check or a more thorough independent evaluation of the design, and it is common to find several different types and levels of design check being carried out on major projects.

5.4 Programme constraints

Perhaps the greatest pressure tending to prevent a thorough and detailed design check is lack of time. This is particularly true in design and build contract situations where the checker will be under pressure not to hold up the construction programme, and in extreme cases this can compromise his ability to make independent judgements. The designer is probably working under even tighter time pressures and may be unable to apply the necessary care to check that design submissions are complete and free from basic errors. The checker is not supposed to be there to find such errors – he is there to check the design – but sometimes it appears that the designer is having to rely on the checker to find the kinds of mistakes that basic quality control would detect. The fault for such situations rests mainly with modern procurement procedures which add ever greater time constraints on all parties in the process.

Sufficient time must be allowed in the project programme, regardless of what type of contract procurement route is being followed. Difficulties arise when a client who does not appreciate the essential added value of a proper check, reluctantly appoints a checker because he is obliged to and does not allow a realistic time for the check activities in the programme at the planning stages.

A typical design and build contract programme prepared by a project manager with no experience of design checking may show a series of design submissions arranged to suit the construction programme, allowing only about two weeks for the checker to check and certify each package. This may be enough for a design review, or even a full check of some elements or some parts of the works but not for all. For a start, there needs to be an initial design submission at the start with all geometry material grades, principal section sizes etc defined to enable the checker to set up and analyse his independent structural model before he can be in a position to check the detailed design packages later. This tends to take much more than two weeks and is often overlooked. It is not realistic to expect a checker to sign a certificate for the design for a multi-million pound project, for which he will share some of the liability, if he only permitted a few weeks to review it.

6. Some other case studies

By way of further illustration the following case studies serve to highlight some of the possible checking arrangements adopted in a variety of very different circumstances.

6.1 The Millennium Dome, London

As in most developed countries, any building in the UK must be subject to a design review by the local authority Building Control department prior to construction. In this case, in recognition of the special nature the Millennium Dome design, the local authority required a more extensive review than usually carried out by Building Control and appointed their own consultant for this task.

However, this was still not considered sufficient for the client and the designer who wanted a full and thorough independent check carried out in a manner similar to the Category 3 check used for major bridges in the UK, in recognition of the considerable added value and re-assurance that such a check provides. Accordingly, the client separately appointed Flint & Neill as independent checker to confirm the suitability of the design criteria and to carry out a fully independent structural analysis and check of the design. This work included checking the geometry of the pre-stressed structure using form-finding software independent of that used by the designer.

Fig. 6 *The London Millennium Dome under construction showing the Blackwall Tunnel vent shaft*

The Dome is constructed around the southern ventilation shaft to the Blackwall Tunnel which carries a major highway under the River Thames. (Fig.6) Part of F&N's role was to independently check the influence of the Dome on the effectiveness of the ventilation shaft. Reassurance was needed that the risks of increasing pollutant levels inside the tunnel were acceptably small. Consequently, our scope included a detailed study of the effect of wind passing over the Dome and the ventilation shafts in a range of speeds and directions, drawing on our experience of the behaviour of wind passing over hills in connection with tall mast and tower analysis.

6.2 Northbank Footbridge, Stockton-on-Tees

In this case, the design emerged through a design competition held by the client in 2002. The bridge has an unusually slender arch structure and as checker we were required to work with the designer to establish suitable critical arch buckling criteria and agree the non-linear analytical techniques required to determine its behaviour.

In addition, the aerodynamic stability of the structure was recognised as of particular concern, and the designer acknowledged his lack of experience in this area. We were able to apply our considerable expertise in this field to assist the designer and verify adequacy through a series of desk studies and wind tunnel tests.

This illustrates another valuable aspect of the independent check, since there will be times, frequently in our experience, when a designer may not have sufficient knowledge and experience of some specific complex aspect of behaviour such as aerodynamics and dynamic response for example. A suitably selected checker can help to ensure that appropriate design criteria are adopted and can add this missing expertise, reassuring both designer and client that the design process being followed is suitable. We are frequently asked to advise specifically on such specialist aspects and to perform independent dynamic response analysis, since this is not necessarily in the daily diet of most practicing engineers.

6.3 Structural Assessment of Erskine Bridge, Scotland

Independent checking applies also to the assessment of existing structures, not just the design of new ones. In this case, Flint & Neill performed the structural assessment of this steel box girder structure and identified the need to develop special assessment criteria since the application of normal design criteria would have been far too conservative and would have resulted in excessive apparent strengthening requirements. [4] The checker, WS Atkins, needed to satisfy themselves that these special criteria were safe and appropriate before either party could proceed with the detailed assessment. Both firms had detailed experience of deriving codified steel box girder design and assessment rules and in the application of reliability theory to determine suitable safety margins, so it was with confidence that we were able to advise our client not to adopt the standard design rules but to use our alternative instead and thus reduce the cost of strengthening from about £20 million to £2 million, as attested by the client at the time. [5]

6.4 Heathrow Terminal 5

Both the client and the designer for Terminal 5 acknowledged that the enormous scale and importance of the roof structure required experience beyond that of most building structures engineers and justifed an independent design check. Indeed it was felt that the family of 196m long steel box roof girders fell more under the scope of the steel box girder bridge rules than any normal building design rules. (Fig.7) Accordingly, F&N was appointed to carry out an independent structural analysis, check the design and advise on aspects associated with the roof erection. Our role was subsequently extended to other aspects of this enormous project, including checking the design and erection of the new control tower.

Fig. 7 *Terminal 5, Heathrow Airport, London*

There is no doubt that the project benefited from the extra comfort and confidence that such an independent check provided, and in the context of such a major project the cost of the check was insignificant. Such independent design checking for major public building structures is now becoming more and more common in the UK and elsewhere.

7. A small price to pay

In the context of the overall project cost, the fee for a full independent check is very small. If valued against the substantial possible costs of rectifying any design problems which may be discovered later, the checker's fee is even more insignificant. It is therefore hard to find a reason not to do it.

For a very low additional cost the client can obtain several added benefits including:

- risk reduction
- extra peace of mind
- confidence that the design criteria are appropriate, especially if the structure or problem is innovative or unusual
- confidence that the design has been properly undertaken in accordance with the agreed criteria
- reassurance that the finished structure, if properly built in accordance with the design, is likely to perform as intended
- another consultant who may share some of the liability in the event that problems arise later

Figure 9 illustrates the typical level of independent design check fees against construction cost taken from real data for a number of real projects. This can be used as a rough guide to Category 3 check fees for bridges of average complexity. The message is clear; for a bridge of value greater than about £10 million a full independent check costs less than half a percent of the cost of construction. When you consider the added value that such a check provides, this is certainly a price worth paying.

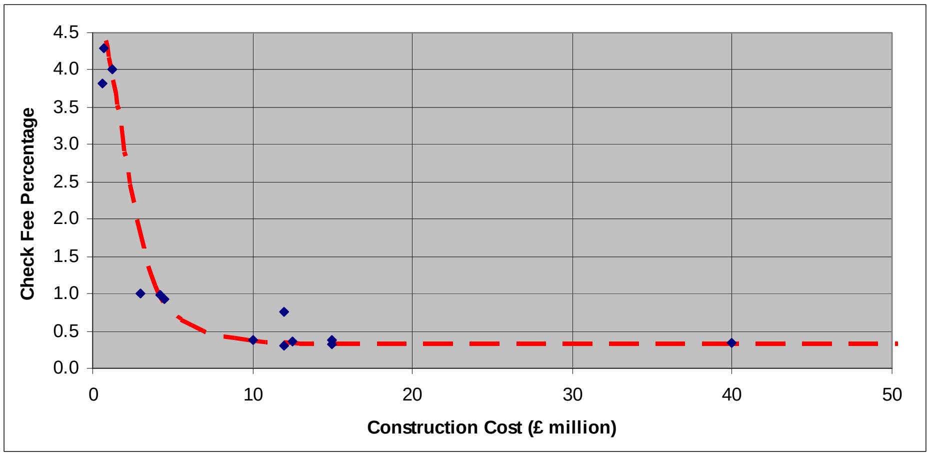


Fig.9 *Typical independent check fees as percentage of bridge construction cost*

For footbridges less than about £2 million, the percentage fee gets high, but the actual cost of the check tends to be reasonably constant, depending on the complexity of the structure. It costs about the same to check the design of a £0.5 million footbridge as a £1 million footbridge as each involves about the same amount of work.

In addition, the checker's role can be extended to include more than merely checking that the design meets the design criteria; for a small extra fee the check could include an economic design review. Thus, instead of just checking that component stress levels are below limiting values he could be asked to comment if they are excessively low. Or to put it another way, the checker's role could be extended to identify over-design as well as any overstress. This is not normally part of the checker's scope, but if included it keeps the designer on his toes to ensure that the design remains economic.

If this approach is adopted, it is very important not to dilute the designer's design responsibility. The designer must be able to ignore the checker's opinion if he wishes to adopt a particularly conservative design approach and keep stresses low in a particularly component for example. The checker's comments should therefore be restricted to reporting where he considers that material could be saved or cost savings could otherwise be achieved without any detriment to the design. This usually means that the checker should merely report where he considers stress utilisation factors are unnecessarily low and leave the designer to decide with the client whether or not a design change to achieve cost savings is appropriate. This approach is only possible if the design and check programmes allow sufficient time for the necessary design review, modification and re-checking to take place. It is also important to recognise that the designer is likely to be working under tight constraints and may not be willing to consider making any design changes.

If the design can be made more economic by this approach, the money saved in construction cost can go a long way towards paying for the checker's fee, even several times over. However, it is probably only worthwhile extending the checker's scope in this way for the relatively large projects. It is unlikely that such an approach would result in significant savings on smaller projects.

8. Certification and shared liability

The independent checker is normally required to certify compliance of the design with the agreed design criteria. This certification carries with it a potential legal liability and is in addition to similar certification provided by the designer. The wording of such certificates is of vital importance and needs to be appropriate to the contractual arrangements and responsibilities for the project.

Certification may take the form of a single final check certificate for the whole design which has been checked, often accompanied by a report describing the main issues and conclusions arising from the check. Alternatively, and commonly in design and build contracts, independent certification may be given in stages for a series of design packages. Either way the checker assumes a degree of responsibility for the adequacy of the checked design.

This is where the true independent design check differs markedly from the design review. Full independent certification of the design requires the checker to carry out a thorough independent check. The legal liabilities of a local authority building control surveyor, for example, who has merely reviewed the drawings and calculations to see that they have been prepared in accordance with appropriate standards, are nothing like so severe. In some parts of the world, a checker is required to stamp the designer's drawings to indicate that they have been checked and in so doing accepts a share of the liability for the design. In order to be qualified to certify drawings in this way a checker must generally be a "Registered Engineer" which requires him to have professional indemnity insurance cover.

In the event of a subsequent failure, clients are theoretically able to pursue an action against both the designer and the checker. In the case of a Category 3 check there will generally be two separate professional indemnity policies each potentially targeted by such an action. However, the share of liability between the designer and checker is a matter for the individuals and the lawyers to decide. I know of very few cases which have been taken to court where a checker has been found liable, so there is little publicly available data available to indicate what shares of liability have been agreed. This in itself is probably a good indication of the value of an independent check. Usually any claims are settled out of court in a commercial settlement. Although there is no hard data on this subject, it is generally considered that the designer-checker liability shares tend to settle in the region of 70:30 or 60:40 respectively depending on the particulars of each case.

It is clear that both parties do not necessarily have equal opportunity to influence the design. The checker is not party to many of the key design decisions and his scope of work may also not extend to a check of all aspects. For example, the checker is not always commissioned to check the materials and workmanship specifications, and if a failure occurs due to some deficiency in these then he cannot be held liable.

However, there is a potential sting in the tail in the UK, since if for whatever reason the designer has gone out of business or is unable to pay, the law allows the checker to be stung for 100% of the claim. It also works the other way of course, and I believe that this "last man standing" arrangement is unique to the UK

In the case of the Ramsgate ferry ramp disaster in 1994, the constructors, designers, checkers and owners were all charged under the UK Health and Safety at Work Act, and the port operators were also charged under the Docks Regulations. The fine for the checker was half the amount for the designer/builder, and both parties were also liable for a roughly equal share of the prosecutor's costs. [7] As a result of this incident, the requirements for checking the design, operation and maintenance of such structures were firmed up in a new CIRIA guide. [8] However, the biggest share of the liability in that case was assigned to the client, and this highlights another important factor, at least in UK law. The client cannot contract-out of his legal liability under current health and safety legislation in the UK.

Laws differ in different countries. Most of mainland Europe works under a civil court system as distinct from the British common law system. In the UK, consulting engineers have a duty to act with due care and diligence and claimants have to prove negligence under the criminal law in order to assign liability which can theoretically be unlimited. Whereas in Germany, for example, engineers typically carry a more stringent fitness-for-purpose obligation, but the levels of liability are somewhat lower. This huge subject is far outside the scope of this paper, but it is important to understand the potential liability issues when accepting an appointment as independent checker (or designer for that matter) in a country whose laws differ from your own.

9. Resolving differences and avoiding conflict

I am often asked "*What happens when the checker and designer arrive at different answers*?" On several occasions I have come across clients not used to a culture of independent checking who have used this as an argument to avoid doing it at all! They refuse the extra confidence and comfort provided by an independent certification of the design because of worries that they might be drawn into an argument between the designer and the checker.

Designers and checkers are first and foremost professionals and they are used to having and resolving differences of opinion. No-one expects the checker to arrive at precisely the same answers as the designer. What matters in the end is their independent professional opinion on the following questions:

- does the design comply with the defined design criteria?
- are the design criteria (including any special departures from normal standards) appropriate?
- is the design properly and clearly defined on the design drawings?

Small differences in analysis results or in calculated utilisation ratios for example are usually neglected as long as they don't affect those opinions.

On the second point above, it is common for the checker to be told the design criteria and not to be asked to check them or offer an opinion as to whether they are appropriate. However, the expert checker may be asked to comment on whether the criteria seem appropriate or whether additional studies are required to develop project-specific criteria. If special criteria are to be developed then it is reasonable that the checker should be asked (and paid!) to review them.

If significant differences arise during the design and check process, the two parties need to exchange opinions, and if necessary the results of their analysis, in order to identify whether one or other has made an error in assumption or calculation. In the vast majority of cases that is as far as it goes. One party makes a correction and that is the end of it. Most often the correction has negligible influence on the cost or programme of the work, but sometimes the result can be significant, depending largely on when it happens. This where it is much easier to resolve any differences under a traditional procurement route where the design and the check are completed prior to inviting tenders for construction. In a design and build situation the cost or programme consequences of late design changes arising as a result of the check can be more significant.

Considering the shared liability issues above, it is clearly in the designer's interest that there should be an independent checker. But more than that, a check provides the opportunity for the designer to gain from the checker's experience to the betterment of the design and perhaps learn new aspects of the engineer's art from his fellow professional. I always relish such opportunities when they arise.

10. Recommendations

I strongly recommend revisiting the recommendations of the Merrison Committee of Inquiry from the early 1970's since the issues they address regarding design and check procedures and the contractual obligations under design and construction contracts apply as much today as they did then. [1] Any aspiring or practicing bridge engineer would do well to read them and also the Report of the Royal Commission of Inquiry into the Failure of West Gate Bridge in Melbourne. [9] These both demonstrate the essential importance of proper design checking.

Where not already established, a culture of independent design checking for bridges should be instigated. Some different models already exist, and the British system represents a good workable model which has been adopted widely and has the benefit of being applied for over 30 years. However, the system may need to be adapted to suit the legal and contractual climate of the country in which it is to be applied.

When undertaking a fully independent design check, the checker should carry out his structural analysis completely independently from the designer, preferably using different modelling and analysis software, and without reference to the designer's calculations.

For large projects, such as major bridges of value greater than £100 million, the scope of work for the independent checker could be extended to include an economic review of the design to identify any areas where cost savings could be made without changing the design intent. However, in such cases the final design decisions must remain with the designer to decide with his client whether any design changes should be made to achieve such cost savings.

The independence of the checker must be ensured. The checker must be free to reach his own independent professional opinion without undue pressure forcing him to certify the design without proper opportunity for rigorous analysis and consideration.

It is vital that design and check programmes allow sufficient time for thorough and rational analysis and consideration to take place. Unrealistic programmes add unwanted pressures on the design and check activities and increase the risk of mistakes being made or errors being missed.

The designer and checker should work in a spirit of mutual respect and co-operation, recognising that they both share the common goal of ensuring a satisfactory outcome for the project, without trying to score points off each other. Both parties have an opportunity to learn from each other and, in the case of innovative solutions, to further the art and practice of engineering technology.

11. Conclusion

It is clear that independent design checking adds considerable value to a project for a very small additional cost. Not only does it add confidence in the design and reduce the risk of failure, it also enables the skills, expertise and experience of the checker to be available to the client and designer for mutual benefit.

The cost of an independent check is typically less than 0.5% of the construction cost for projects greater than about £6 million sterling. A good checker if appointed to undertake an economic design review at the same time as the design check can easily save more than his fee several times over in the case of major projects.

It is very rare for designs which have been independently checked to cause serious problems. Statistically, there are many more cases of structural failures or inadequacies arising due to poor design when there has been no independent check than when an independent checker has been appointed. Even if problems do occur with a checked design, the presence of the checker means a sharing of the liability which is in both the client's and the designer's interest.

Rigorous design checking procedures introduced a generation ago in an attempt to reduce the incidence of structural failures arose as a result of painful lessons learnt from history. If future failures are to be prevented then those lessons need to be re-learnt, and if necessary the checking procedures instigated then may need to be modified to suit current and future practices taking into account new and developing legal and commercial constraints.

12. References

[1] "*Inquiry into the Basis of Design and Method of Erection of Steel-Box Girder Bridges*" Report of the Merrison Committee of Inquiry, HMSO, London 1973.

[2] WOODS C.ROLAND, "*Building Regulations (London)*", The Structural Engineer, April 1934

[3] BD2/05: "*Technical Approval of Highway Structures*", The Design Manual for Roads and Bridges Vol.1, the Highways Agency, August 2005

[4] FIRTH I.P.T., ADAMSON R.N., and HUBAND M.V., "*The Refurbishment of Erskine Bridge, Scotland*", IABSE Symposium, Melbourne, September 2002

[5] BRODIE A., "*The Bridge Assessment and Strengthening Programme in Scotland*", *Bridge Rehabilitation in the UK*, The Institution of Civil Engineers, October 2000

[6] "*Steel Box Girder Bridges*", pp.3-5, Proceeding of the International Conference at the Institution of Civil Engineers, 13-14 February 1973.

[7] "Learning from Construction Failures" (Chapter by J. Chapman) Whittles Publishing 2001

[8] "*Safety in Ports – Ship to Shore Linkspans and Walkways*" CIRIA Report C518, 1999

[9] "*Report of the Royal Commission of Inquiry into the Failure of West Gate Bridge,*" published by the Government of the State of Victoria, Australia, 1971.