

Whether to Strengthen ? Risk Analysis for Strengthening Decision-Making

Robin Spence and Andrew Brown
Cambridge Architectural Research

Philip Cooper
Cameron Taylor Bedford

1. Introduction

Across the country, thousands of industrial and utilities buildings are in use which were built before current wind loadings were in force and appear to be exposed to regular recurrence of high windspeeds, which could in the future become both higher and more frequent (Graves and Philipson, 2000). Many of these are ageing and have some degree of deterioration through corrosion or fatigue of cladding fixings. Yet for the economic activities which they accommodate, they provide appropriate and cost-effective workspace, and their replacement by structures built to modern codes cannot be afforded in the near future.

Frequently, when such buildings are analysed under the environmental loads now specified for new buildings, one or more members are shown to be overstressed and are deemed to be in need of strengthening or replacement. This would be costly and disruptive; and it is entirely incorrect to class a structure as unsafe because, using a elastic analysis, one or more members is shown to exceed permissible loads or stresses. However, Facilities Managers need to comply with the Health and Safety at Work Act, and cannot ignore structural engineers' reports which appear to condemn the structures as unsafe. But no more realistic framework for a risk analysis is available. In these circumstances, what is the best way forward ?

Based on recent practical experiences, this paper suggests that a relatively simple risk analysis combined with an equally straightforward structural failure analysis can be used to identify whether such structures are unsafe and constitute a risk to life; such an analysis can also identify both priorities for strengthening among a number of buildings, and in addition show which strengthening options are likely to be most beneficial in reducing expected losses from high wind.

A method for conducting such an investigation is proposed. It is also suggested that structural engineers need to decide on an acceptable and probability of collapse risk for such structures, so that a clear criteria for intervention can be classified.

2. The method

The proposed method has the following six components, elaborated in the following sections:

- 1 Define a set of damage states with increasing consequences for direct and collateral loss.

- 2 Determine the range of loads (windspeed, snow depth) and load combinations (with crane loads) which would/could be expected to give rise to each damage state, and draw up vulnerability curves for each damage state.
- 3 Determine the annual or 50-year exceedence probability of loads or load combinations over the whole range of loads needed to cause the defined damage states.
- 4 Perform risk calculation for each damage state; compare outputs with HSE and other risk norms.
- 5 Quantify consequences of each damage state in terms of total cost (building repair plus collateral damage costs plus loss of production), and expected casualties/loss of life, and calculate annual probabilities.
- 6 Identify strengthening needed to reduce risks to an acceptable level; estimate costs and reduction of annual risk probability and benefit/cost ratio.
- 7 Prioritise works needed in order of:
 - Reducing existing risk levels to workforce or production
 - Financial return of undertaking works.

3. Assessment of the Structure and Failure Scenarios

Each damage state is defined in terms of the state of the structure after the event. Six damage states defined as follows is in many circumstances an appropriate number, though this may vary according to the type of structure being examined:

- D0 No damage
- D1 Slight damage: damage to gutters, signage, security lighting, loose tiles or flashings etc; easily and cheaply repairable.
- D2 Significant damage; partial detachment of small amounts of cladding or roof sheets etc; broken windows, damaged doors or door mountings etc; fall of a few ceiling panels; more costly with some collateral damage and impact on production. Repairable.
- D3 Severe damage: significant areas of cladding or roofing removed; fall of a significant numbers of ceiling panels; failure of individual joints; small permanent deformation; significant collateral damage; likely casualties to building occupants, requiring production to be halted. Technically repairable, though not necessarily economically worth repairing
- D4 Failure: buckling of individual roof truss or stanchion members, significant permanent displacement of purlins or sheeting rails; loss of most cladding or roofing sheets and ceiling panels; major collateral damage; some casualties among workforce; production removed to alternative location. Building unlikely to be repairable.
- D5 Collapse; failure of substantial numbers of joints or primary structural members; major collateral damage; significant casualties among any occupants, major disruption to production. Not repairable..

Site investigations are then needed to determine the layout and sizes of typical elements which are considered critical to the crossing of each damage state threshold. These include major and secondary structural members; bolts and welds at typical joints; cladding and roofing materials and fastenings; and the location of stability elements such as cross-bracing and masonry walls.

On the basis of this investigation, calculations are made for each building to determine the range of loads (windspeed, snow depth) and load combinations which would/could be expected to give rise to each damage state.

From these calculations, and making assumptions about the likely variation in the parameters used in the calculations, vulnerability relationships are prepared for each building in each damage state, giving the probability of that damage state occurring under a given wind loading (site gust windspeed) or snow load, and any important combinations (these loads in combination, or in conjunction with crane loads) with a significant probability of occurrence, taking into account the configuration, orientation and grouping of the buildings.

4. Assessment of the Loadings on the Structure

In the UK, the principal environmental loads on the structures are normally wind load and snow load. These should be combined where appropriate with dead loads and other normal operational loads eg crane load.

Exceedance probability curves (hazard curves) for windload and snow load for any UK site at an appropriate range of annual exceedance probabilities can be developed using

- the BS windspeed map and modifiers defined for the sites in the current wind loading code (BS6399, 1997, Part 2)
- snow loading data provided in the Snow load code (BS 6399, Part 3) as modified by recent work at the Building Research Establishment (Brettle, 2002, and Brettle and Currie, 2002).

5. Assessment of the Risk of Failure

Risks of each damage state have been calculated for each structure by convolution of the vulnerability and hazard curves defined above. By calculating the collateral costs of each damage state, risks are presented on an annual probability basis, allowing separate structures to be prioritised for action.

For those structures identified as having a high priority for action, strengthening measures can be identified as a part of an upgrading strategy. Based on approximate costs of such upgrading work and the resulting reduced risk levels, an estimate of the benefits, costs and benefit-cost ratio for upgrading can also be obtained.

6. Application to industrial sheds

6.1 The context

A particular application of the method concerned an industrial enterprise being conducted in a range of clad steel framed sheds dating from the period 1940 to 1978. There were 10 buildings, with floor areas ranging from 1000 m² to over 10,000 m², each with a different structural system, and with contents and operations of different value being carried out in them. An example of the axonometric sketches developed for each structure is shown in Fig 1.

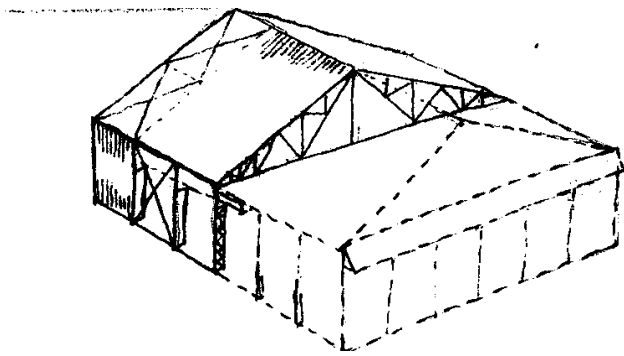


Figure 1. Typical shed structure – axonometric sketch

6.2 Damage states

Following the definition of the damage states given above it was decided that the surface loadings on the structure leading to damage states D2 to D5 could be defined in terms of the loading required to reach specific failure states as follows.

- Damage state D2 was defined by the sheets and their connection to the structure
- Damage state D3 was defined by the loads causing local deflection or failure of purlins sheeting rails, brick walls or other secondary structure
- Damage state D4 was defined by loading causing major failure of purlins and sheeting rails, or some distortion or local buckling of the primary structure
- Damage state D5 was defined by failure of the primary structure, either through collapse of the cross-bracing or main truss or stanchion members.

Damage state D1 is not amenable to direct calculation and a different approach to assessing the risk of D1 was adopted, based on the windspeeds which have been found to cause minor damage in industrial structures in the UK, and the number of recorded incidents, using BRE data (Mootoswamy and Baker, 1999, Buller 1978, Menzies, 1971).

6.3 Vulnerability, loading and risk

For each building a set of vulnerability curves was developed, showing the probability of each separate damage state being exceeded. An example is shown in Fig 2. The exceedence probability for the site basic windspeed was derived from BS6399 1997, Part 2, and is shown for this location (at which the 50-year basic windspeed is 23 m/s) in Figure 3. (Bayesian comment ??) Annual risks for the exceedence of each damage state were calculated by convolving the vulnerability and hazard curves. These calculations made allowance for the expected distribution of the wind forces on each structure, and the number of structural elements exposed to the highest loading at each damage state.

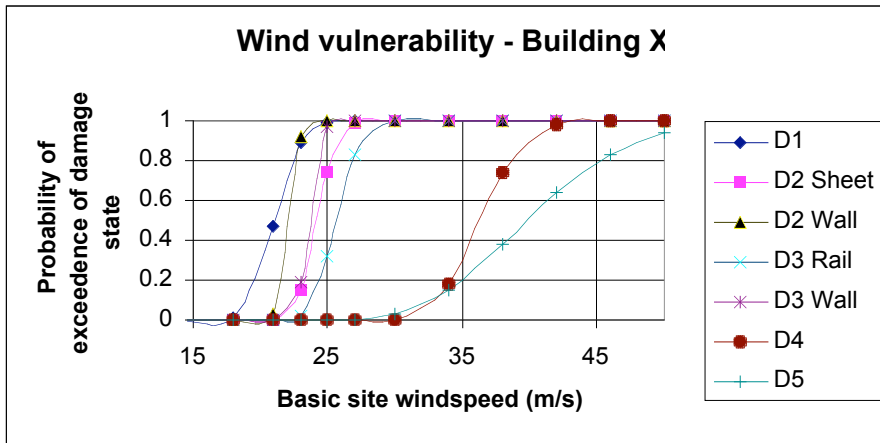


Figure 2. Wind vulnerability – probability of occurrence of each damage state and condition as a function of basic site windspeed.

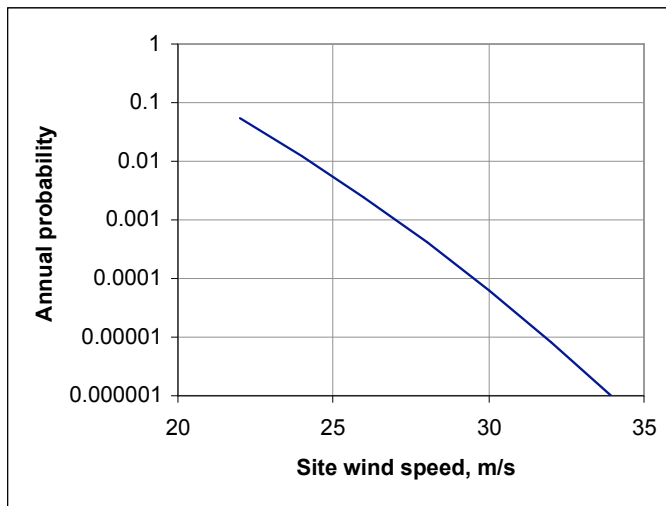


Figure 3. Wind hazard - Annual probability of different windspeeds at the given site

In addition to the annual risk of exceedence of each damage state, including the risk of collapse, the annual risk of death or serious injury to each employee was calculated, based on the anticipated consequences of collapse.

On the basis of these calculations it was concluded that, for the structures considered, the annual risk of collapse under the load combinations examined was nowhere greater than 0.5×10^{-5} , that the annual risk to each employee of death was less than 1×10^{-6} , and of serious injury less than 1×10^{-7} .

HSE (2001) defines a risk of death of 10^{-6} as “broadly acceptable”; risks of this order are considered

“insignificant and adequately controlled. HSE as regulator would not normally require further action to reduce risks”.

There is no comparable regulatory advice on the acceptability of the risks of structural damage or collapse, but the literature suggests that annual risks of around 1×10^{-4} are

normal for many classes of structure (Melchers, 1999), so risks below this level may be considered acceptable.

6.4 Valuations and loss levels

The method was also used to estimate annual financial losses for each structure, and to identify which strengthening actions might be considered beneficial in reducing these losses. This involved obtaining from the client, and the clients insurers, the valuation for each structure of:

- Repair or strengthening of damaged elements
- Replacement of the entire structure
- Contents, inventories and work-in-progress
- Business interruption costs
- Numbers of employees present at different times
- Likely costs associated with fatality or serious injury

Although none of these quantities can be identified with certainty, their estimation is helpful in establishing whether action is likely to be needed, and what the priorities for action should be.

6.5 Outcome

Some aspects of what these calculations revealed in this particular case, which are likely to be of general relevance were:

- Most of the annualised loss was not associated with major structural failure, but was connected with cladding failure, which it was found was liable to occur at windspeeds with a return period around or below 100 years. Such failure could have significant consequences for business interruption and damage to sensitive contents, even though posing only small risks to human health or life
- Contents losses and business interruption together constituted over 90% of the calculated losses; building repair or replacement was less than 10%.
- Total annual risks of around 0.5% of rebuilding costs and less than 0.1% of the total valuation were found to be substantially lower than a typical insurance premium.
- The calculations on loss levels and loss rates are highly sensitive to basic wind speed assumptions. An increase in the assumed basic windspeed at the site of only 1 m/s (about 4%), would be enough to double all losses.
- For several particular structures in which particularly high-value operations were being conducted, it was shown to be cost-effective (in reducing annual losses) to strengthen sheeting rails or replace cladding, with annual benefit to cost ratios exceeding 10%.

7. Conclusions

1. A method has been proposed by which it is possible to produce information in a form valuable for building owners and their facilities managers on risk levels and strengthening priorities.
2. Where high-value industrial operations are being conducted, losses are generally associated with contents and business interruption rather than building damage and repair.
3. The risks calculated are highly sensitive to basic wind speed and other parameters – some framework for investigation of the results of future climate change is

therefore needed, and the chosen approach could have an important significance for this kind of investigation.

4. Although all codes implicitly use such assumptions, there is at present no explicit guidance available for structural engineering calculations on what is an acceptable risk of structural failure at different damage levels for different classes of structure. The structural engineering profession (SCOSS) needs to consider this problem in association with HSE, in order to guide decision-making on the safety and future life of existing structures.
5. The method proposed is relatively straightforward, does not depend on advanced structural analysis, and could be used for a wide range of existing building types and associated risks.

References

Brettle M E & Currie D M, 2002. Snow Loading In The UK And Eire: Ground Snow Load Map, *The Structural Engineer*, 80/12, 18 June 2002

Brettle M E, 2002. A Revised Ground Snow Loading Map For The UK, *The Structural Engineer*, 80/22, 19 Nov. 2002

BS6399, *Loadings For Buildings: Part 3 Code Of Practice For Imposed Roof Loads*, British Standard Institution, 1988

BS6399, *Loadings For Buildings: Part 2. Code Of Practice For Wind Loads*, British Standard Institution, 1997

Buller, P.S.J, 1978. *Wind damage to buildings in the UK, 1970-76*, BRE CP 42/78, Building Research Establishment

Graves, H, and Phillipson, M.C, 2000. *Potential implications of climate change in the built environment*, Building Research Establishment, East Kilbride

Health and Safety Executive, 2001. *Reducing risks, protecting people*, HMSO London

Mootoswamy, V.K.S and Baker M.J, 1998. *Wind damage to Buildings in the UK*, Loss Prevention Council.

Melchers, R.E, 1999. *Structural reliability, Analysis and Prediction*, John Wiley, Chichester.

Menzies, J.B, 1971. *Wind damage to buildings in the UK, 1962-1969*, BRE CP 35/71, Building Research Establishment