SENSITIVITY OF THE RESPONSE OF STRUCTURES TO FIRES AND EXPLOSIONS

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1. INTRODUCTION

The main objective of the work presented in this paper, was to determine the important parameters for calculating the capacity, response and probability of failure (or 'Reliability') of structural members to thermal and/or blast loads and to calculate the 'Sensitivity Factors' associated with the resistance and load variables. In this context the 'resistance' variables may include applied static loads.

The objective was set to enable the HSE to determine which effects are important in the calculation of structural response and to enable them to identify submitted safety case analyses which are likely to be inadequate as a result of omissions of important considerations. SLP, as a contractor and operator, has also benefited as the identification of important factors in the calculation leads to the development of efficient methods, where spurious considerations are not included in the analysis.

In order to perform the sensitivity analyses it was necessary to develop an analytical method of accurately calculating the response of structural members to fires and explosions so that numerous response calculations could be performed quickly. This allowed response surfaces to be created which characterise the response to a wide range of values of the load and resistance variables. These response surfaces form part of the required data base for the calculation of sensitivity measures which quantify the importance of particular variables.

A recent ERA paper[1] has identified a number of weaknesses in the single degree of freedom blast response method originally proposed by Biggs[2]. These are mainly associated with assumed fixity conditions and interaction with support structures. The present work has gone some way towards overcoming these problems by explicitly incorporating various fixity conditions and applied loads into the method of analysis of typical members and panels. The members, panels and modules examined were the same as those chosen by the safety working group which functioned as part of the recent joint industry project on fire and blast[3,4,5] .

The main conclusions of the investigation into the effects of fixity and imposed loads will be presented in a later paper.

2. SENSITIVITY - VARIABLES AND METHODOLOGY

The sensitivity of structural response was examined for the following variables:-

1. The level of static in plane loads on columns.
2. The level of out of plane, equipment loads and masses on main floor and ceiling beams.
3. The rotational stiffness of supports at member ends.
4. Variations of Young's modulus and yield stress for blast exposed members and blast exposed members at elevated temperatures[6].
5. Variation of secondary moments due to permanent deflection from blast loading on members exposed to fire.
6. Variations of lateral resistance from membrane effects.
7. Variations of emissivity of steel and fires and variations of the distance of members from fires.

The sensitivity of the response of a structural member to thermal and blast loads with respect to a particular variable, for example yield stress, is intuitively dependant on the slope of the graph of response plotted against yield stress. The higher the slope, the higher the sensitivity of response. If we are considering blast response, the mid-span displacement of the loaded column would be a suitable measure of response. Unfortunately the slope of the response will depend on the units chosen for the independent variable 'yield stress', denoted by 'x' in Figure 1. Also shown in this figure is the probability density function for yield stress from data made available to SLP by British Steel. This shows the expected range of values of yield stress and its expected variability. This range enables the slope of the response curve to be interpreted in terms of a length scale associated with the range of variability of the yield stress. This leads to the idea of variable standardisation or normalisation of variables.

A suitable measure of the variability of the yield stress about the mean μ_X is the standard deviation of yield stress or x , σ_X the response graph may then be re-plotted in terms of a normalised variable z_X defined by:-

$$z_x = \left(x - \mu_X\right) / \sigma_X$$

Now z_X is a dimensionless variable whose value represents a variation from the mean value with a well defined probability of occurrence if the probability distribution function of x is known. Probability distributions of selected resistance and load variables are given in Reference 8 together with suggested values for the statistical parameters such as mean and standard deviation.

In using the above equation it is assumed that x and z_X are both Normally distributed variables. Other types of distribution, such as Gumbel, Weibull or Lognormal may be standardised by applying the inverse normal distribution function to the cumulative probability function for *x*. Standardisation creates a dimensionless variable whose value gives a measure of the distance from the original variable's mean value, hence giving a precise indication of the likelihood of occurrence of the value of the original variable. Note that the dimensionless nature of the standardised variable allows direct comparison between variables of different types and units.

It should be noted that in some cases the mean value of a variable is not used in design. For example, the mean value of yield stress is not necessarily that taken for design, it is the actual expected value from a large number of measurements made on the particular steel type used.

The same transformation to normalised variables may be made to load variables such as blast peak overpressure and radiation flux. In this way the sensitivity of response to variations of load may be meaningfully assessed. In practice a failure criterion will be chosen such as limiting deflection. This will give rise to a failure curve (in two dimensions) such as that shown in Figure 2. This curve divides the fail and pass regions of the load and resistance variables. Normalisation of the load and resistance variables will mean that the slope of the failure curve will be a meaningful measure of the Sensitivity of the response to variations of both the resistance variable *x* and the load variable *y*.

3. RELIABILITY AND PROBABILITY OF FAILURE

3.1 General

The probability of failure of a member under fire or blast loading will naturally be dependent on the applied loads and the values of the resistance variables associated with the member. The variables affecting member resistance may be the yield stress and Young's modulus of the steel, the length of the member, the emissivity of the steel or the end fixity conditions. Each of these variables can take a range of values - the values that each variable may take will be defined by a statistical distribution. The probability that the member will fail will depend on the way each variable affects member response and the range of values each variable may sensibly take.

3.2 Description of the Direct Probability Method (DPM)

The process of determination of member reliability and sensitivity is illustrated in Figure 3 for the blast response of a column. The resistance variable in this case was the eccentricity of the applied static axial load. The methodology is illustrated in Figure 3.

The probability distributions of the load and resistance variables were first identified from published results[9] and for each value of the load and resistance variables, a 30 x 30 response matrix was calculated. For blast loading, the response was taken to be the maximum deflection of the member, whilst for fire loading the response was taken to be the capacity of the member to withstand the static loads applied to it. The matrix represented the response of the member under every likely value that the load and resistance variables may take. In practice, the variables were varied by 3 standard deviations either side of their mean values. This gave a 99.8% level of confidence that all the values that are likely to occur have been examined. A typical response surface is shown in the first box of Figure 3 and for a different case in Figure 4.

A failure criterion was then chosen for the member corresponding to the load type. In the case of blast response, failure was assumed to be the exceedence of a limiting deflection. This may be chosen to be a limiting deflection associated with plasticity, the limiting strain or it may be associated with a non-structural performance criterion such as the avoidance of impact with piping or equipment. For fire loading, the failure criteria was simply the collapse of the member under the applied static loads.

A pass/fail surface is then calculated by applying the failure criterion to the response matrix. In this case the limiting deflection is subtracted from all cells of the response matrix. Positive values now correspond to the pass situation. This is shown in the second box of Figure 3. The ‘pass’ and ‘fail’ regions of the matrix are divided by a ‘failure line’. The way in which the slope of the failure line varies along its length reveals the relative effect the load and resistance variables have on member response at failure.

The load and resistance variables are then *normalised* or *standardised* at this stage using the equation given above.

The probabilities of occurrence associated with each cell in the ‘fail’ region of the pass/fail surface were then calculated as shown in the fourth box of Figure 3. Combination of the probability distribution surface and the failure response surface gave the probability of failure surface shown in the figure. The probabilities were then summed for cells in the failure region to give the probability of failure of the member at a given load level or the partial probability of failure curve, shown in the box at the foot of Figure 3. Summation of probabilities over all load levels gives the overall probability of failure of the member.

An advantage of the above method is that the entire range of values that the load and resistance variables are likely to take is used in the analysis. The 30 x 30 response matrix provided sufficient resolution to accurately calculate member reliability. To refine the calculation, linear interpolation was used between cells to accurately determine the position of the failure line.

3.3 Comparison with conventional Reliability Theory

The ‘reliability index’, as described in conventional reliability theory, is the minimum distance of the failure line from the point corresponding to the mean values of the load and resistance variables. This distance is calculated using standardised variables. The value of the reliability index, denoted by β, and the failure probability are connected by the following equation:

$$p_f = \Phi(-\beta)$$

This process is illustrated in Figure 5.

In the cases where the failure line was relatively linear, the probability of failure calculated using numerical methods was very similar to the values calculated using the reliability index. However, if the failure surface is non-linear, the reliability index method will not give accurate results.

If more basic load or resistance variables are identified then the original response surfaces may be ‘post-processed’ to give the sensitivity of response to the new variables. For example, the analysis of pool fires allowed the original load variable ‘thermal radiation’ to be converted to variables such as fuel release rate, the emissivity of the fire and distance of the member from the fire. This process allows the probability of failure as well as the sensitivities of response to each load variable to be calculated without the need to recalculate the response surfaces.

4. SENSITIVITY OF RESPONSE - RANKING OF KEY VARIABLES

The aim of this work was to determine the relative importance of each variable when calculating fire and blast response, and hence to prioritise the variables. This was done by calculating the *sensitivity* of response to changes in each variable. The sensitivity is a measure of the contribution a variable has on the response of a member, through the amount of variation in the response resulting from a change in the variable.

In First Order Reliability Methods (FORM), sensitivity is a measure of the slope of the failure line at the ‘Design Point’ (Figure 5). The design point represents the most probable point on the failure line. This point is actually the nearest position of the failure line to the mean values of the load and resistance variables. The value of sensitivity is normalised so that a sensitivity close to zero means that the variable has no significant effect on member failure, and a sensitivity close to 1 means that the variable entirely determines the failure of the member. Sensitivities of different variables, even if their units are different, can be directly compared with each other. This allows the effect that each variable has on member failure to be placed in order of importance, and hence different resistance and load variables may be prioritised.

The software developed by SLP allowed sensitivities of response to both load and resistance variables to be calculated anywhere on the response surface. However, the sensitivities at or near the failure point are generally of most interest as they represent the most likely conditions should failure occur.

FORM assumes that the failure line is linear, and hence that the value of sensitivity calculated at the design point represents the behaviour of the failure function away from the design point. Although in the majority of cases examined in this work the failure line was nearly linear, in some cases this was not the case. An example is the sensitivity of blast response to blast duration, where the response surface oscillates for different values of duration. This leads to a failure line which also oscillates as shown in Figure 6, where the gradient of the line varies from positive to negative. As the sensitivity to a particular variable is a measure of the gradient of the failure line, the sensitivity also varies from positive to negative along the failure line. For situations such as these, an average value of sensitivity over the length of the failure line was calculated. Probability weighting was used along the failure line so that the values most likely to occur contributed most to the sensitivity calculated.

The slope of the failure line and hence the sensitivities associated with it may be highly dependent on the failure criterion used. For example, if the failure displacement for blast loading is in the elastic regime then the sensitivity to variations in yield stress may be zero. However, if the failure displacement is taken to be the onset of full plasticity, the sensitivity to yield stress may be relatively high.

In some cases two resistance variables may interact with each other. For example, interaction may occur between the variables ‘in-plane load’ and ‘load duration’ for blast loading on a column. The in-plane load on the column affects its natural period. The response to blast loading is dependent on the load duration to natural period ratio, and hence both in-plane loads and load duration will have a similar effect on member response. Interaction effects cause the failure *surface* between the two variables and the load variable to be curved. If significant interaction occurs then 3 dimensional response volumes must be calculated for the 3 variables concerned, so that a full 2 dimensional failure surface is created. However, this approach results in a large increase in the number of simulations required. Three dimensional response volumes have been calculated in some cases, details of which are contained in references 8 and 9. In all the cases detailed in this paper no significant interaction between variables was observed, and hence the results calculated using one load and one resistance variable at a time are valid.

The range of values which the load and resistance variables can take will significantly contribute to the failure probability of a member. For example, the mean blast pressure applied to a member may be much less than the member’s capacity, but the member may still have a significant probability of failure.

5. RESULTS

A number of sample members have been subject to a full sensitivity analysis. For each of the members chosen, 900 simulations were performed for each resistance variable over a wide range of blast and thermal loading conditions. The sensitivities calculated for each resistance variable have been presented as pie charts, which clearly show the relative contribution of each variable to member failure.

The relative sensitivities of a typical column to blast loading are shown in Figure 7. It can be seen that the eccentricity of the axial load applied to the member and the yield stress of the steel are the most important factors affecting member reliability. The eccentricity creates a bending moment which can severely reduce the blast resistance of the member. In addition, the eccentricity was assumed to be able to take a relatively wide range of values which is largely a result of the variation of applied static end moments. The yield stress dictates the size of the plastic moment capacity, and hence its value directly affects the maximum resistance of the member. The stiffness of the column is inversely proportional to the cube of its length, and hence variations in member length have a relatively large effect on the column response. The response of the column is relatively insensitive to Young’s modulus, as member stiffness is only proportional to its value. Axial load has a smaller affect on member response than eccentricity only because its value is likely to be distributed over a smaller range.

The relative sensitivities of a typical floor beam to thermal loading are shown in Figure 8. The response of the beam is most sensitive to the emissivity of the steel. This is an important result as the value of emissivity of a steel member is not accurately known, and hence care must be taken when calculating member response to thermal loading. The degree of equipment loading is the second most influential factor, as it directly affects the maximum moment applied to the beam. Yield stress is also important, as its value affects the original moment capacity of the beam. It can be noted that the response of the beam is insensitive to Young's modulus, as the beam collapses due to a reduction in moment capacity and not due to a reduction in stiffness.

Figure 9 shows the relative sensitivities of a 3m panel to blast loading. The response of the panel is dominated by the yield stress of the steel. The resistance of the panel increases until its elastic capacity in tension is reached. As an upper bound capacity is being sought for the panel, widespread yielding is assumed to occur. This contrasts with a hinge line approach which would give rise to localised yielding and lower capacities. The resistance and hence the panel capacity at which this occurs is directly dependent on the yield stress of the steel. Span, plate thickness and Young's modulus contribute an approximately equal amount to the response of the panel.

The response of a typical column to pool fire loading is shown in figure 10. The pool fire was modelled so that 'basic' variables such as the emissivity of the flame, the mass release rate and the distance of the fire from the column could be explicitly considered. It can be seen that the axial load applied to the column is the most important factor contributing to member failure. An initial eccentricity was assumed, so that the axial load applied to the member created a P-delta moment. In addition, the axial load reduced the moment capacity of the column. The distance of the fire from the member is also important. For the purposes of the analyses, a relatively small variation in distance from the fire was assumed. In fact, the position of the fire may be able to take a wide range of positions, and hence its position will largely dominate the thermal response of the member considered. This is particularly true for ventilation limited compartment fires. The emissivity of the flame has little effect on the member.

6. CONCLUSIONS

1. A method has been developed which enables the prioritisation of the parameter and effects to be taken into account in the calculation of structural component response to fires and explosions. The method also gives the probability of failure of a component given the acceptance criterion and probability distributions of the load and resistance variables.

2. It has been found that there will be a finite probability of failure for a component even though the capacity may be greater than the mean of the pressure probability distribution. The design value for overpressure is at present identified by a pressure level with some ill-defined exceedence probability. This needs to be defined in some way acceptable to the industry.

3. The most important parameter in determining thermal response of beams and columns is the emissivity of the steel, which is only an estimate which will depend on the surface properties of the material at the time.

4. Static imposed load eccentricity was found to be the most important parameter in determining the blast response of a column.

5. The Direct Probability Method (DPM) described in this paper may be applied to any situation where the load is defined by a statistical distribution. Typical examples in Offshore Engineering would be the calculation of response to wave and wind loads.

6. The method will be used to determine which effects are important in the calculation of structural response and enable the identification of safety case analyses which are likely to be inadequate as a result of omissions of important considerations. The contractor and operator will also benefit from the use of this method, as the identification of important factors in the calculation leads to the development of efficient methods, where spurious considerations are not included.

7. REFERENCES

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8. Baker M. & Corbett G., ‘Structural Reliability Analysis and its Application to Offshore Structures’. Lecture Course available from Prof. Baker of Aberdeen University, Department of Engineering, 1994.

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FIGURES

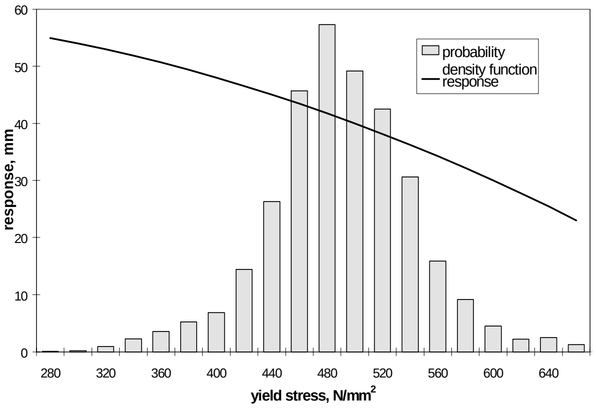


Figure 1: Typical variation of blast response with yield stress

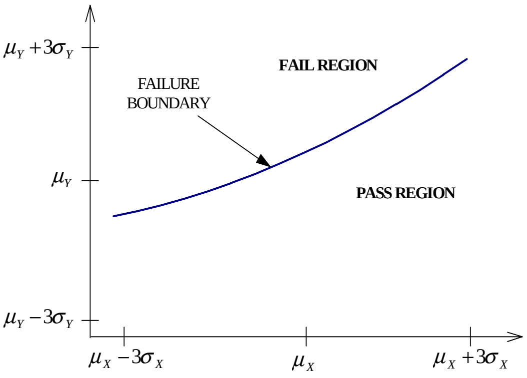
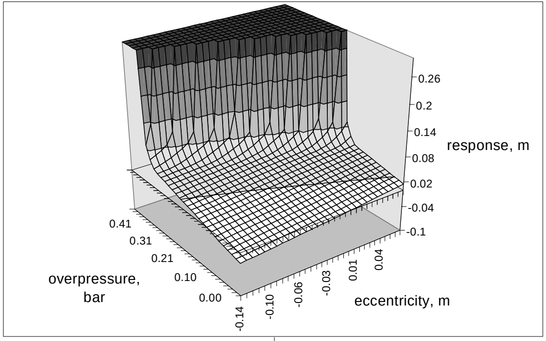
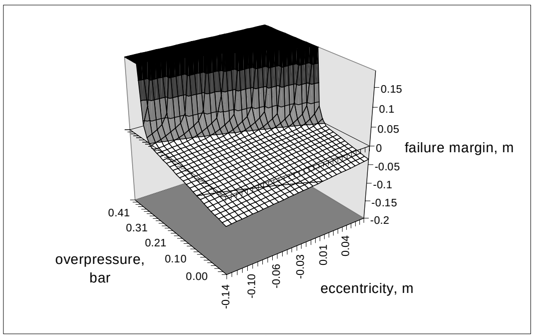


Figure 2: Typical failure curve

CALCULATE RESPONSE TO RANGE OF POSSIBLE FIRE/EXPLOSION LOADS

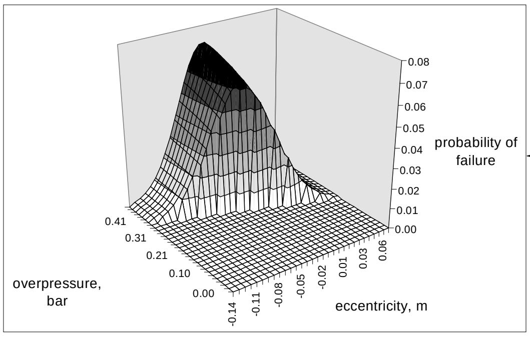


FAILURE RESPONSE SURFACE

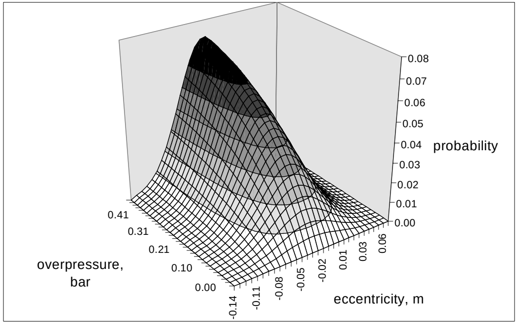


FAILURE CRITERION

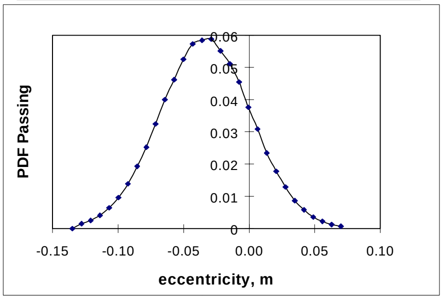
PROBABILITY OF FAILURE SURFACE



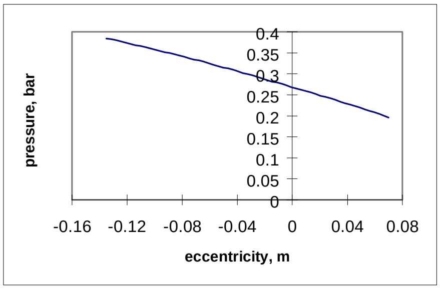
LOAD/RESISTANCE PROBABILITY DISTRIBUTION



PARTIAL PROBABILITIES OF FAILURE



FAILURE BOUNDARY LINE



FAILURE PROBABILITY

SENSITIVITIES FOR RESISTANCE VARIABLES

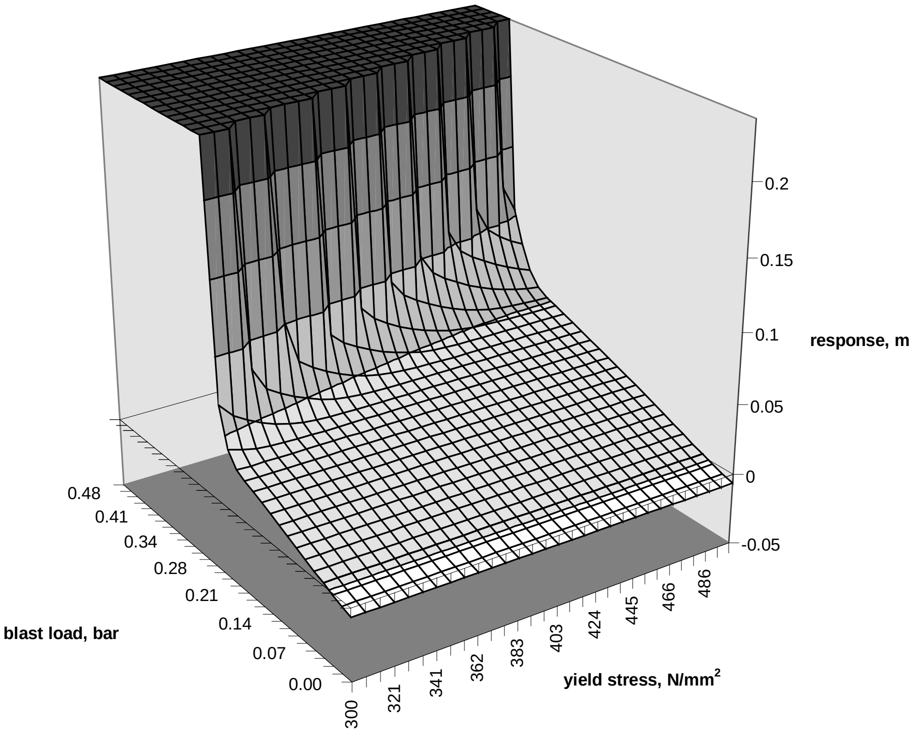


Figure 4: Typical response surface

Figure 5: Definition of 'Design Point'

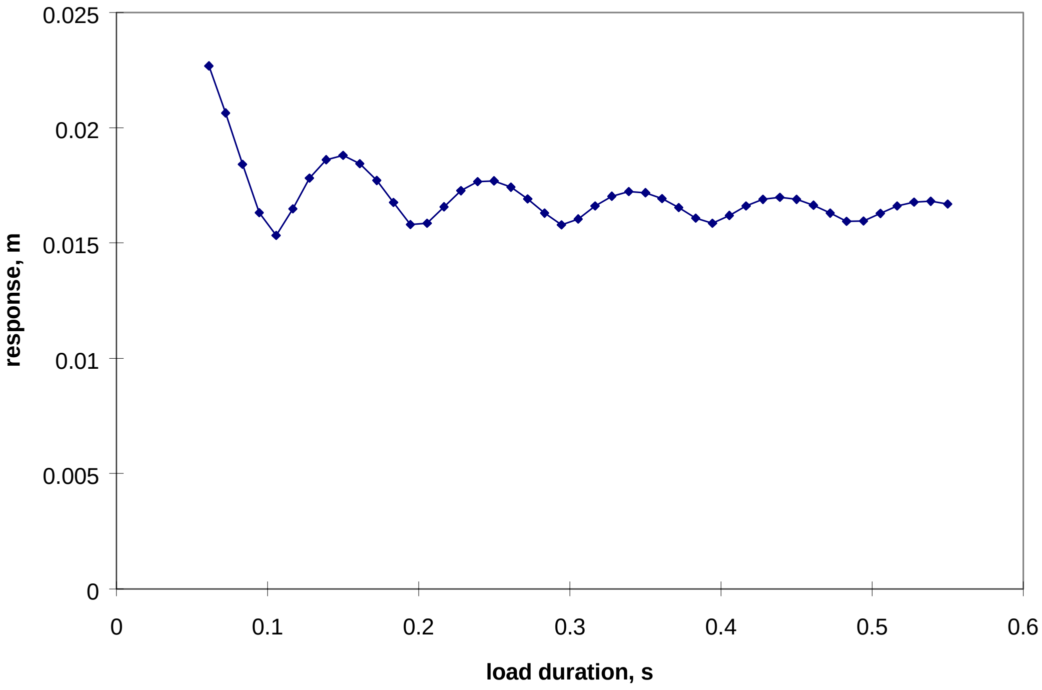


Figure 6: Failure line for load duration

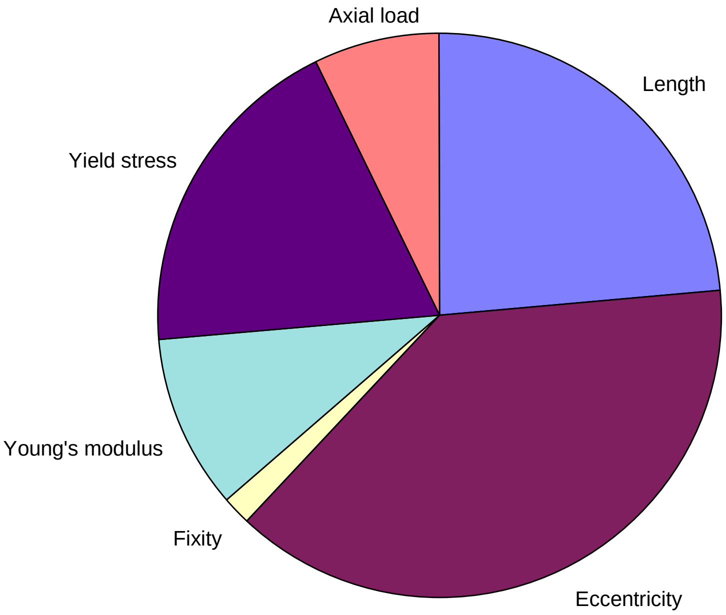


Figure 7: Sensitivities of column response to blast loading

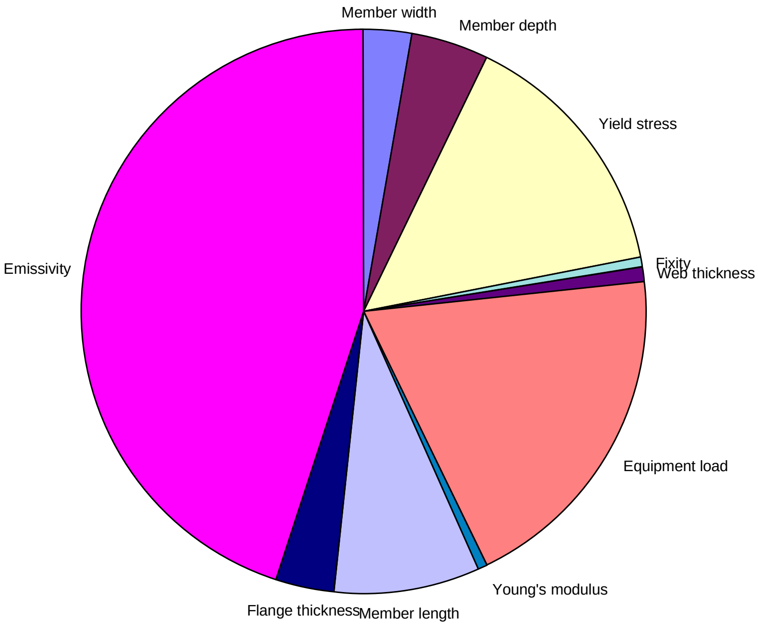


Figure 8: Sensitivities of beam response to thermal loading

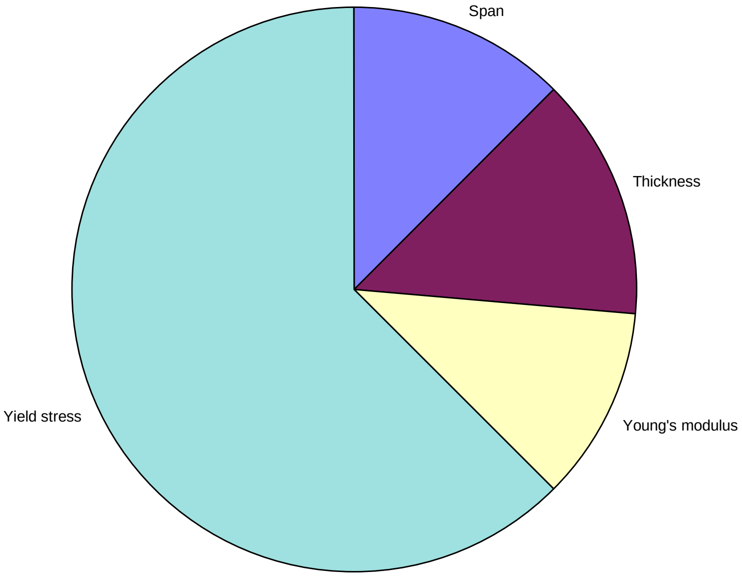


Figure 9: Sensitivities of panel response to blast loading

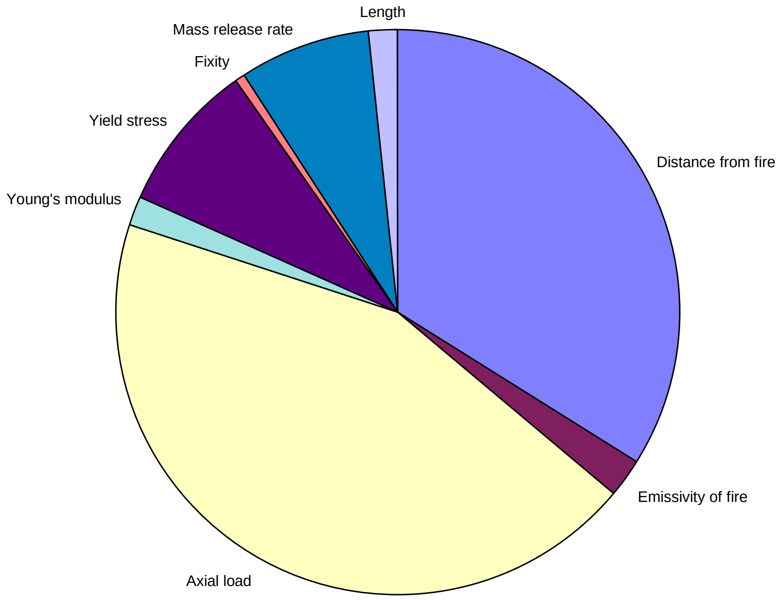


Figure 10: Sensitivity of column to pool fire loading