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A Load Redistribution Approach for Enhancing Robustness in Highly Optimized 3D Spatial Frame Structures

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Abstract
An analytical process is developed to appraise and enhance the resistance to disproportionate collapse in 3D space frame structures in an economical manner. Studies were undertaken on a new industrial facility designed for construction in France, a 70m tall and 265m long, rippled barrel vault space frame. A load redistribution approach is adopted based on nominal element removal to measure and enhance the robustness of the structure whilst minimising the additional structural weight required. To simulate the instantaneous dynamic response of a damaged model, a dynamic load factor (DLF) is applied to the axial forces determined in the space frame elements. This process developed within a computational design workflow, measures DLF during nominal member removals by an advanced explicit time history analysis. The approach demonstrates that a highly optimised 3D space frame can have sufficient resistance to disproportionate collapse whilst maintaining a low-carbon configuration.

Keywords: Spatial Structure, Disproportionate Collapse, Robustness Design, Explicit Analysis.

1. Structural design configuration for persistent cases

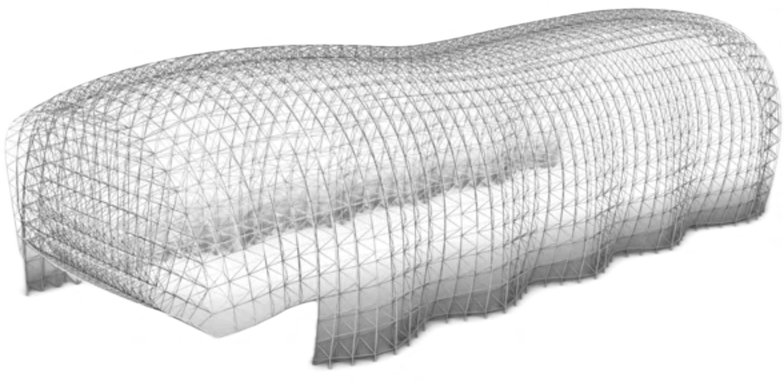

Figure 1: Render of 3D space frame

Studies were undertaken on a new industrial facility designed for construction in France, a 70m tall and 265m long, rippled, barrel vault space frame, consisting of approximately 13,000 steel tubular elements. The design of the structure for the persistent load cases utilised a number of in-house configuration and analysis algorithms to optimise the geometry of the steel frame. This produced a structure of minimal weight, cost and embodied carbon, whilst respecting the constraints of building volume and fabrication efficiency based on an optimal number of nodes.

The mild steel circular hollow section(CHS) members intersect at cast spherical nodes. The ends of the circular hollow sections terminate in a tapered steel cone which has an internal threaded connection for bolting into the node. This connection is assumed to allow rotational freedom with the forces between elements being transferred by in-plane axial loads only.

2. Disproportionate collapse overview

Robustness of the structure is measured considering its ability to withstand accidental design actions and susceptibility to disproportionate collapse. Typically, approaches to design against disproportionate collapse fall into one of two categories from [1, Sec. 4.6] as in figure 2:

- Load protection; in which measures are taken to guard against the loss or damage of elements occurring.
- Load redistribution; in which the ability of the structure to redistribute the loads resulting from loss or damage of local elements is enhanced

Often, load redistribution methods are preferable because this has the beneficial effect on both the extent and severity of collapse against events of unspecified cause or increasing magnitude.

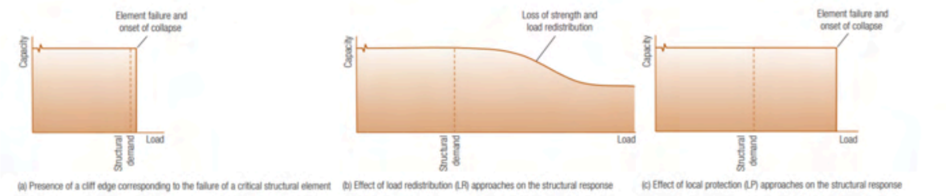

Figure 2: Effect of load redistribution and load protection approaches to enhancing robustness against disproportionate collapse © IStructE Manual for the systematic risk assessment of high-risk structures against disproportionate collapse

2.1. Load redistribution method

High member utilisations under ULS load combinations meant that the slender steel tube elements had inherently low resistance to withstand out-of-plane accidental impact loads. Member 'protection' was deemed unviable based on the significant uplift in total steel weight, cost and embodied carbon of the structure that it would result in. Therefore, a load redistribution approach based on nominal element removal was adopted to measure and enhance the robustness of the structure. Owing to finite computational resources, a strategy was developed to ensure that upon simulated removal of a single element, no other member in the structure would fail.

Elements are designed to be non-critical, ensuring the structure is capable of re-distributing the load as loss of strength and yielding of an individual member occurs. Guidance from [1, Sec. 4.3.3] states that alternate load path approach assumes a hypothetical damage state that has led to the critical loss of one single element while no other failing members.

The transition from the original structural configuration to the damaged state is assumed to be instantaneous, exposing the structure to dynamic effects. Therefore, a dynamic load factor (DLF) is applied to the axial forces determined in the elements of the damaged model. Typically, a dynamic load factor (DLF) of 2.0 is assumed under linear static state for capturing the dynamic effects of the damaged model [1, Sec. 4.9.2].

However, the authors conducted explicit time history analyses of the structure to verify and confirm this assumption. Effective tying between all elements is provided as required in Annex A of [2], with the minimum effective tie force taken as 75kN.

2.2. Load combinations for robustness studies

The studies into robustness against progressive collapse of the structure are based on an accidental loading scenario. Due to the complex usage of the building, a large number of load combinations and cases including loading of moveable and variable imposed loads, i.e. rear crane positions, monumental door loads, result in heavy computational time of the study.

Simplified assumptions in (1) and (2) representing frequent and quasi-permanent combinations are made for studying the robustness of the space frame derived from EN 1990, in order to reduce the number of possible load combinations.

$$1.0\,SW + 1.0\,SDL + 1.0\,LL + 0.7\,Q_k + 0.2\,SL/WL \quad (1)$$

$$1.0\,SW + 1.0\,SDL + 1.0\,LL + 0.7Q_k \quad (2)$$

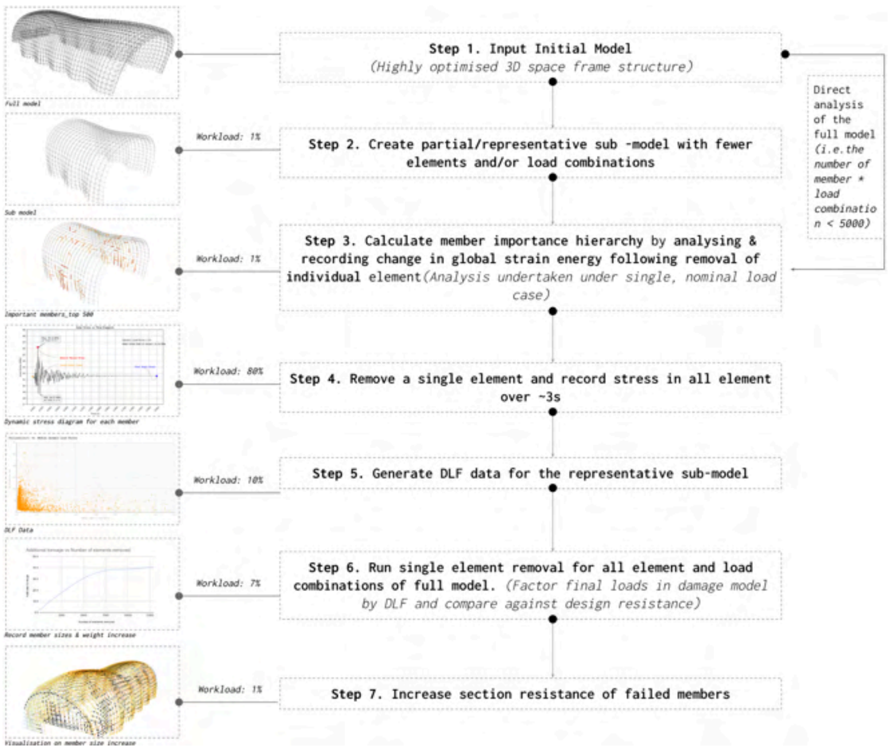

Figure 3: Flow chart of the computational workflow of load redistribution method

2.3. Computational workflow of load redistribution method

A process presented on figure 3 is established for carrying out nominal element removal analysis of the space frame elements using a linear static analysis under frequent and quasi-permanent accidental load conditions. Each element is removed in turn, with the axial forces in all remaining elements recorded. Elements which exceed their accidental design capacity in the damaged models can have their cross-section increased in order to achieve the required capacity.

2.4. Analysis method

A linear static procedure is used to perform alternate load path analyses of the structure on the step 4. A linear static analysis is assumed to be a viable method as the structural space frame system dictates that elements typically remain elastic, i.e. there is relatively little capacity for plastic hinging to occur at the 'pinned' nodal ball joints.

The linear response of members subject to the applied load curve representing a nominal member removal are calculated and recorded by the linear time history solver on Oasys GSA [3]. The methodology for modeling damping is detailed in Section 3.4.2; the magnitude of member stresses and overall structural response are notably influenced by the specific damping parameters applied.

3. Calculation of Dynamic Load Factor (DLF)

3.1 Development of sub-model

Due to computational constraints, studies are undertaken based on a scale version of an idealised space frame: the space frame model comprises approximately 5000 elements with a scale of one-third of the full model as shown in figure 4 (left). The structure is optimised in Karamba3D to achieve a total mass and relative stiffness equal to the actual space frame. The geometry of the framing is subtly altered from that of the actual building. The structure is designed to be symmetrical about major axes removing irregularities in tubular cross-sections and stiffness across the structure. This helps to reduce the complexity of displacement mode shapes under loading.

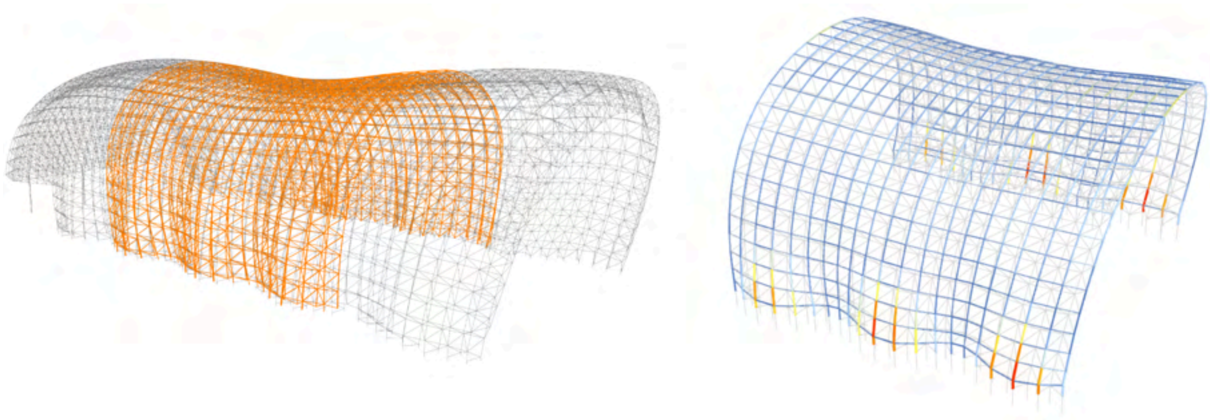

Figure 4: Sub-model of 5000 elements used to study dynamic load factors highlighted in orange (left), and sub-model importance hierarchy analysis with most important members in red (right)

3.2. Member importance hierarchy analysis

A member importance hierarchy of all the elements in the space frame is established following the steps from [4, secs. 2-3]. The member importance hierarchy helps to identify those elements in the structure which are likely to be most consequential following their nominal removal.

Member importance is determined by assessing the change in global axial strain energy of the structure following nominal removal of each element, subject to two nominal loadcases: unit load vertically (LC0) and laterally (LC1).

The figure 4 (right) highlights those elements which are found to result in the greatest change in global axial strain energy. As anticipated, those elements which are 'most important' correlate generally with the members towards the base of the space frame where axial forces in ULS design situations, and subsequently cross-section sizes are greatest.

3.3. Dynamic load factor calculation

Studies are undertaken to assess the variation in magnitude of dynamic load factor that may occur in the structure, when subjected to the nominal removal of an element. Compared to over-conservative instantaneous member removal, research [5, sec. 1 and 5] has concluded that the non-instantaneous removal time of 1ms is a reliable fail-safe value for simulating damage events, thus each iteration of member removal of the space frame structure is applied as a dynamic axial load decreasing from 1.0 to 0 within 1ms under the accidental impact load as in figure 5 (left).

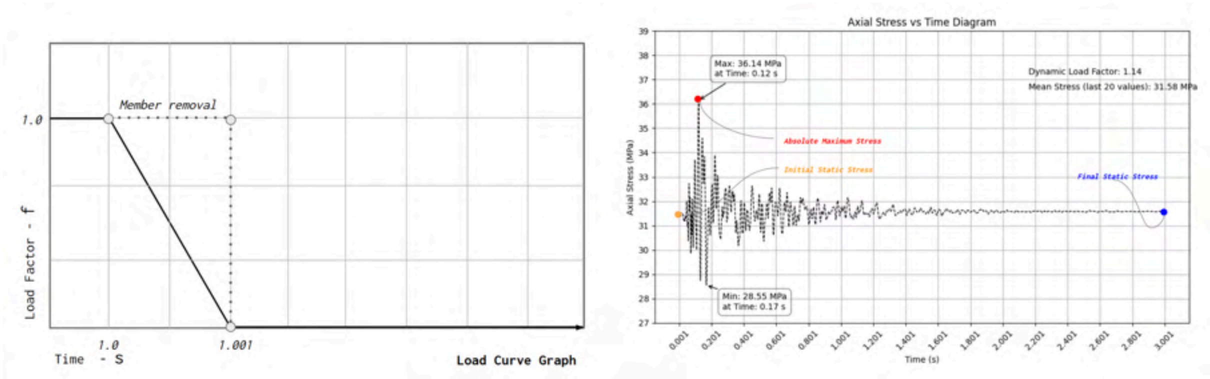

Figure 5: Diagram of member removal as loading curve in 1ms (left), and dynamic load factor calculation following the dynamic effects of member stress in 3s after member removal (right)

The other members' axial forces are recorded immediately following the removal of a single member as a 0.005s time step until the new redistributed loadpath is settled as in figure 5 (right). The peak dynamic load factor for each element is found by the ratio between the extreme force in the member immediately after the removal of another element, compared to the final static state.

$$DLF = \frac{\sigma_{max,dynamic}}{\sigma_{final,static}} \quad (3)$$

3.4. Explicit time history analysis

3.4.1. Explicit time history analysis model

A linear time history analysis of the undamaged structure is performed to determine the initial axial forces present in each member for each load condition under consideration. A unit of horizontal and vertical load cases is applied to the frame as two characteristic loading cases.

3.4.2. Damping sensitivity study

In the analysis, damping is incorporated through the application of a Rayleigh damping curve in Oasys GSA during the initial phases of nominal element removals.

The approximate value of logarithmic decrement of structural damping for steel buildings under fundamental modes is 0.05 from the table F.2 in [6], therefore the damping ratio applied is 0.796%.

The method and magnitude of applying critical damping are found to substantially impact the output values of DLF from the initial studies. Furthermore, due to the complexity and scale of the structural frame, accurate damping ratios for both high frequency and low frequency modes have proved difficult to correlate accurately using the logarithmic decrement method.

For example, the persistent global mode is significantly affected by the mass (M) and damping characteristics (C) of the system; this part of the response remains after the transient effects have decayed and persists as long as the periodic excitation continues showing in figure 6. The transient local response is typically more sensitive to the stiffness (K) and damping characteristics (C), so that it oscillates rapidly to a static state before the global mode settles after 2s.

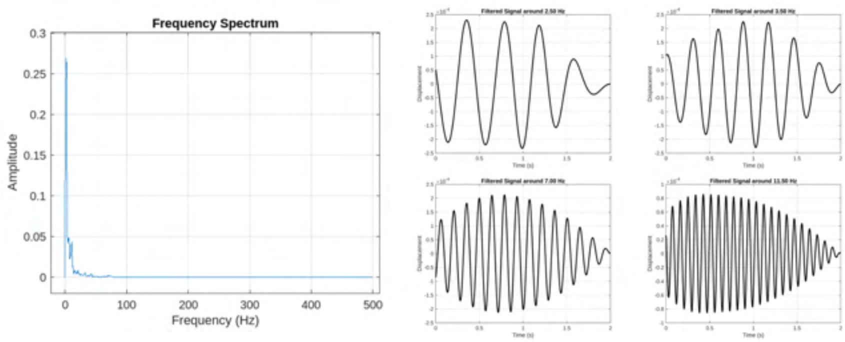

Figure 6: Dynamic frequency spectrum and signal separation of a typical member following nominal removal

$$Mu + Cu + Ku = pf(t) \quad (4)$$

There are two typical methods of applying damping to the linear explicit time history model:

- Rayleigh damping curve shown as equation (6):

  It correlates damping to both mass and stiffness by a critical damping curve as in equation (5)

$$C = \alpha M + \beta K \quad (5)$$

$$\xi_i = \frac{1}{2\omega_i}\alpha + \frac{\omega_i}{2}\beta \quad (6)$$

- Viscous damping (damper element):

  The damper element's matrix only describes viscosity without stiffness and mass in GSA.

The following three damping modeling approaches are explored in order to correlate the applied damping ratio and the resultant calculated damping measured by frequency modes in each member as shown in figure 7:

- Rayleigh damping model and pinned node (Rayleigh damping curve)
- Damper element & pinned node (Viscous damping)
- Damper element & rigidly linked node (Viscous damping and rigid node)

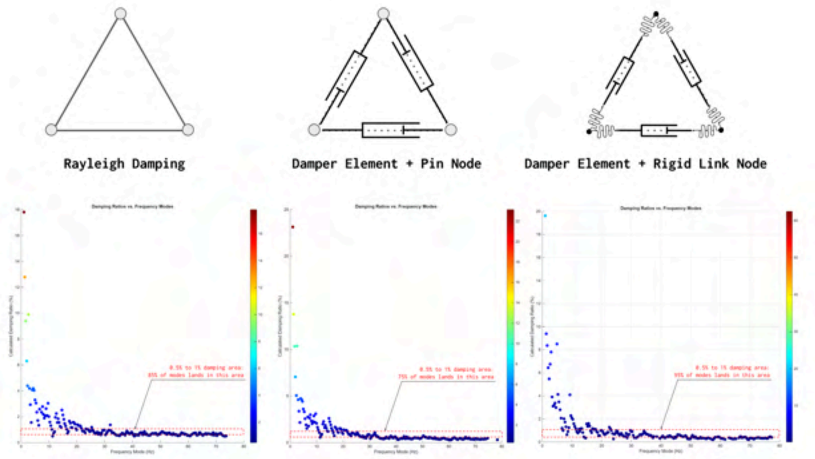

Figure 7: Study of comparing the damping model on member and node

The modeling method of the damper element and rigid node was adopted because it exhibits a stronger correlation with the applied damping ratio as in figure 7. Compared to the pinned node mode, the rigid link model introduces additional kinematic constraints and different dynamic motion between damper elements while still allowing rotation freedom of a typical steel node. Also, the non-uniform global distribution of Rayleigh damping due to mass and stiffness results in uneven energy dissipation throughout the structure, thereby contributing to larger variations in the DLF.

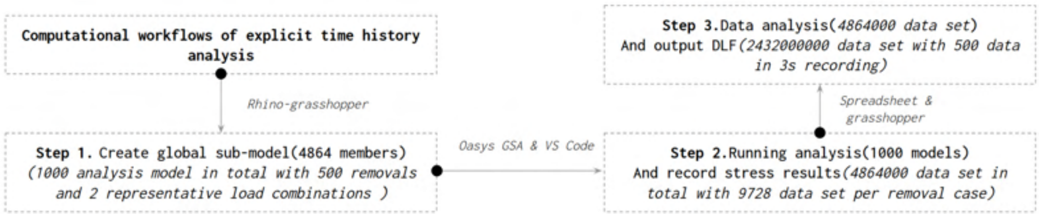

Figure 8: Computational workflows of the linear time history analysis

3.4.3. Computational workflow

The figure 8 illustrates the computational workflow of the linear time-history analysis conducted in Oasys GSA. VScode was used to automatically change analysis parameters, control the solver and output stress values, creating an automated process from geometric model generation to the extraction and analysis of the DLF dataset.

3.5. Dynamic load factor (partial) results

Calculation of dynamic load factors in this method is computationally very heavy. Of the 5000 elements in the sub-model studied, only the top 500 elements (10%), ranked based on the importance hierarchy, have been nominally removed as shown in figure 9. Since the elements removed are those previously known to have the most substantial effect, it is considered that the results presented are likely to be slightly conservative compared to the full dataset.

In many instances, there is data which must be disregarded, where high dynamic load factors are reported where stresses on the element are very low. These occur when there is close to zero axial force initially in the element, and hence any increase in the load is reported as a very high dynamic load factor. These instances are attempted to be removed from the final data set by comparison of the reported dynamic load factor and the utilisation of the element.

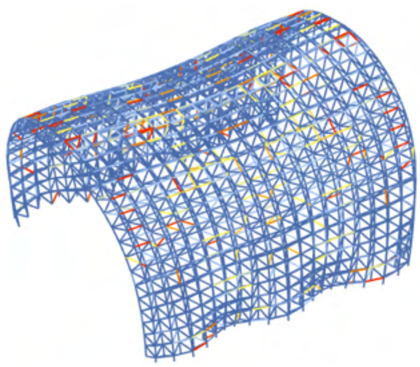

Figure 9. Plot showing distribution of element median values of dynamic load factor

From the data initially collected it has been difficult to establish clear patterns in the magnitude of dynamic load factors in elements across the structure. One correlation appears to be between the value of dynamic load factor and amplitude of modal response at relatively low frequencies, however further study across a larger subset would be required to verify this.

The mean value dynamic load factor is found to be 1.7. However, figure 10 and 11 shows that the majority of dynamic load factors in all instances is much closer to 1.0.

- The median value for dynamic load factor in the data collected is 1.3.
- 91% of the median values of dynamic load factor for each element are < 2.0 (the standard assumed DLF value within load distribution procedure).
- 82% of the median values of dynamic load factor for each element are < 1.5.

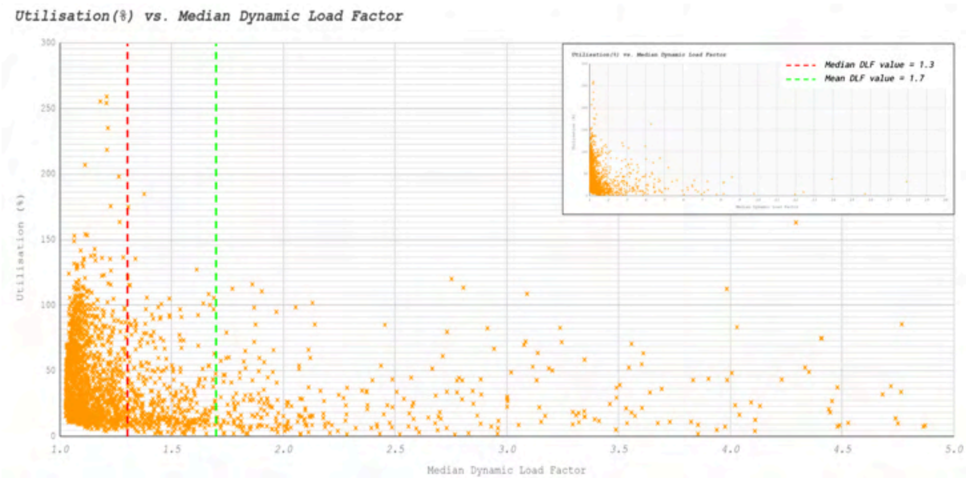

Figure 10. Dotted chart showing the utilisation of element(%) against the median dynamic load factor (DLF)

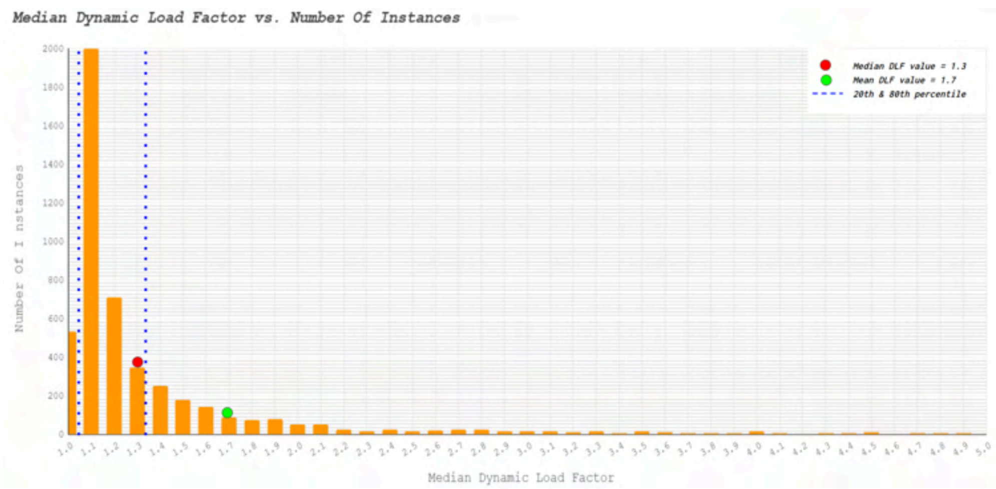

Figure 11. Column chart of the number of instances for dynamic load factors (DLF) from 1.0 to 5.0

4. Robustness design assessment

4.1. Utilisation of elements following nominal removal

A dynamic load factor, chosen from the previously established analysis studies, can subsequently be incorporated into nominal element removal cases of the full building space frame. Following the sequential removal of one space frame element at a time the maximum tension and compression forces in each member (accounting for dynamic load factors) are recorded. The maximum axial forces are compared to the design resistance of the element in accidental load conditions.

Where the maximum axial force is found to exceed the design resistance of a member in accidental load conditions, then that member is subsequently redesigned. This results in the element cross section increasing in size and/or weight and the total weight increase of the space frame is recorded. The results of this analysis are shown for a select number of applied dynamic load factors as figure 12.

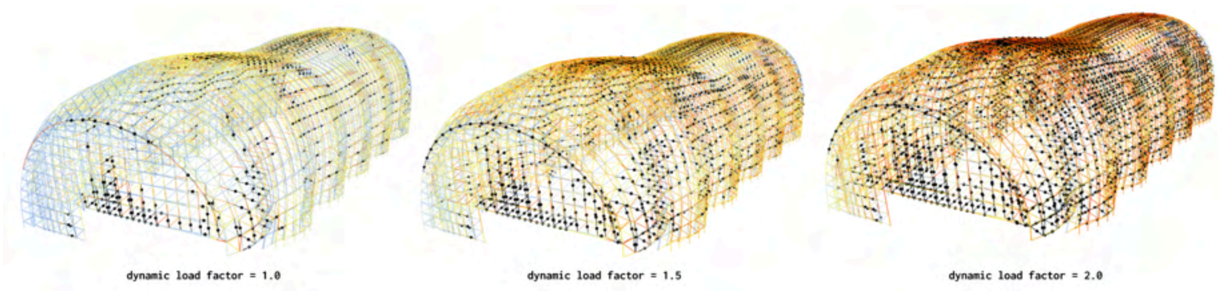

Figure 12. Plot showing element utilisation following nominal element removals for dynamic load factor of 1.0, 1.5 and 2.0 (failed elements in black)

4.2. Summary of implication of dynamic load factor

The table 2 indicates the effect that the applied dynamic load factor has on the number of failing elements and the subsequent weight increase of the space frame.

Table 2: Effect on increase in tonnage for varying dynamic load factor values

Dynamic load factor	Number of failed elements	Additional frame weight (tonnes)	Additional frame weight (% total)
2	3818	99.79	6.22
1.9	3323	83.17	5.18
1.8	2863	69.65	4.34
1.7	2479	58.70	3.66
1.6	2120	49.46	3.08
1.5	1813	41.05	2.56
1.4	1536	33.53	2.09
1.3	1312	27.94	1.74
1.2	1101	22.09	1.38
1.1	887	17.04	1.06
1.0	700	13.02	0.81

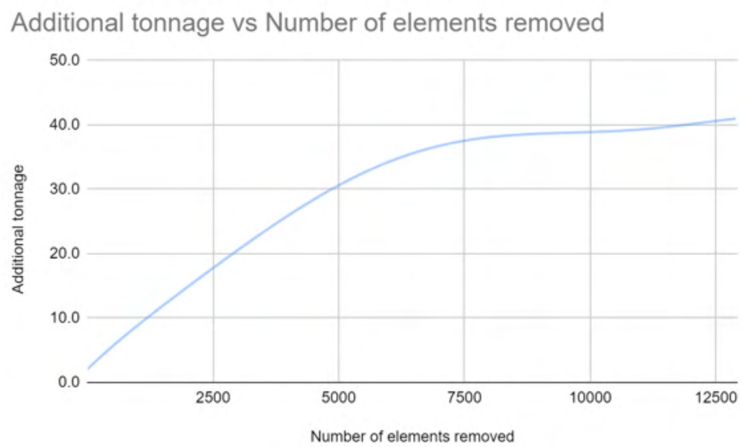

Figure 13. Chart showing increase in required tonnage of space frame compared to the number of elements removed (when sorted by importance) for a dynamic load factor = 1.5

Figure 13 indicates the relationship between member importance and their impact on the remaining frame when nominally removed. The results are provided, considering a dynamic load factor of 1.5. It can be seen that the top 1% of members (sorted by importance), when nominally removed, result in 7% of the total weight increase of the frame. Once the top 50% of the elements have been nominally removed, 85% of the total increase in frame weight has occurred.

5. Conclusion

This paper presents a load redistribution methodology for enhancing resistance to disproportionate collapse, by calculating the Dynamic Load Factor (DLF) and accessing its material efficiency for a highly optimised three-dimensional spatial frame structure in practical engineering applications.

It has been shown that a relatively computationally heavy alternate load path analysis can be used to avoid the need for adoption of less efficient methods, i.e. load protection and compartmentalisation.

Studies have shown that attributing a dynamic load factor of 2.0 would be appropriate for conservative design which satisfactorily accounts for the dynamic response of the frame from undamaged to damaged state.

The average and median values for the dynamic load factor across a space frame structure may be well below 2.0. Adoption of a lower value can dramatically reduce the increase in material, cost and embodied carbon when reviewing a structures' resistance to disproportionate collapse

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