The Importance of Dynamic Effects in Progressive Collapse

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Summary

This paper presents a methodology to assess the extent of damage to a multi-storey structure following localised collapse. This is accomplished through the design of an algorithm to track progressive collapse in a structure and its implementation as a computer program. The algorithm is based on the alternative path method of analysis. Individual elements are systematically removed from the structure, and these altered structures are analysed to determine the extent of the resulting collapse. By considering the effects of damage to all members in a structure the algorithm can identify whether a structure is unduly sensitive to the effects of localised damage. In order to accurately model the progression of collapse through a structure, it is necessary to consider dynamic effects. The algorithm is extended to include dynamic effects and calculate the corresponding increased bending moments and shear forces.

Keywords: robustness; progressive collapse; accidental actions; elasto-plastic analysis; dynamic analysis; alternative load path; structural reliability; vulnerability analysis.

1. Introduction

Progressive collapse is defined by ASCE 7-05 [1] as *"the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it"*. More generally, progressive collapse is characterised by the loss of load-carrying capacity of a relatively small portion of a structure. This initial damage triggers a cascade of failures, affecting a major proportion of the structure. A collapse of this nature can be triggered by many causes; including design and construction errors, as well as loading conditions with a low probability of occurrence (e.g. gas explosions, vehicular collisions). However, the unforeseen nature of these events presents the designer with a significant challenge when trying to improve structural safety.

Due to recent developments in computerised design, and high-performance materials, modern structures are more optimised than their predecessors. This optimisation has led to a reduction in the inherent margin of safety. The result of this is that modern structures have little excess capacity to resist unforeseen loading conditions. Therefore, modern structures are more vulnerable to unforeseen loading conditions. Gross and McGuire [2] suggest that this increased vulnerability can also be attributed to new construction methods which aim to reduce costs, but lack the strength and continuity of traditional forms of construction. Additionally, the increased threat of terrorism worldwide has highlighted the need to consider hazards that may not have been viewed as significant in the past. One of the most serious risks associated with this increased vulnerability is the risk of collapse. Although this is a significantly rare event, it is widely appreciated that, regardless of the triggering event, structural collapse is the principal reason for injury and death in building failures [3]. Therefore, the incorporation of rational procedures for mitigating the potential for collapse must be incorporated into the design of all structures.

Fig. 1: Ronan Point apartment tower after collapse

The intellectual debate on progressive collapse, and the robustness of structures, was initiated following the partial collapse of the 22-storey Ronan Point apartment tower. On the morning of May 16, 1968, a minor gas explosion, on the 18 floor, blew out the exterior walls of the apartment [4]. This triggered a progression of failure that resulted in the collapse of the southeast corner of the tower. As a result of this event, and the consequent report of the Commission of Inquiry, a number of countries (including the UK and Canada) implemented provisions to minimise the potential for progressive collapse. The terrorist attack on the Murrah Federal Office Building, in 1995, marked the start of a second wave of interest in the topic. Following the collapse of the World Trade Centre Twin Towers, and the nearby World Trade Centre 7 building, on September 11, 2001, interest in this subject appears to have reached its peak. Numerous publications on progressive collapse and extreme loading have appeared in the literature over recent years, and a number of guidance documents have been published by regulatory authorities to assist design professionals in designing progressive collapse resistant structures [5-6].

2. Methods of Improving Progressive Collapse Resistance

As building designers cannot possibly design for every hazard that a building may be subjected to in its lifetime, a general design approach is required to account for the risks associated with low-probability high-consequence events. There are, in general, three alternative approaches to designing structures to resist progressive collapse:

- Improved interconnection or continuity;
- Alternative load path method; and
- Improved local resistance.

These approaches are normally classified in terms of indirect and direct design approaches.

2.1 Indirect Design

Indirect design approaches consist of various prescriptive measures of improving the robustness of a structure. These methods have the advantage that they can be implemented without the need for any additional analysis. This is a significant benefit when dealing with unforeseen loading conditions, and therefore indirect design methods are incorporated into most major codes and guidelines [1, 5-7]. When applying this approach, the overall structural robustness is increased by adopting general methods of improving structural integrity, throughout the design process. The provisions are usually in the form of prescriptive requirements for minimum joint resistance, continuity and tying between the members.

This approach is often adopted in the form of minimum tying force requirements [7]. These requirements are based on the underlying philosophy that if all members are connected by joints with a specified capacity, the selected structural configuration will have adequate strength to resist progressive collapse. Hence, the structural elements should be effectively tied together to allow redistribution of the gravity loads following a local failure. In general, both horizontal and vertical ties should be considered, the capacities of which are determined separately to the design loads. Additionally, horizontal ties should be arranged in continuous straight lines and distributed throughout the plan of each floor in two directions, at approximately right angles, and vertical ties should be continuous from the lowest to the highest level of the building.

However, these approaches give no consideration to how a structure should behave if local damage occurs, and therefore may not actually increase the resistance of a structure to progressive collapse. Therefore, it is advised that these techniques are only used for standard structural configurations, and that a more detailed analysis would be carried out for complex or high occupancy structures [8].

2.2 Direct Design

In contrast, direct design approaches rely heavily on structural analysis and can benefit significantly from the use of sophisticated analysis techniques; such as, nonlinear and/or dynamic analysis. Two commonly applied approaches to reduce the potential for progressive collapse are; the specific local resistance method and the alternative load path method. The specific local resistance method increases the strength of key elements to resist failure under certain specified loading conditions. While, the alternative load path method requires a structure to be designed so that it can bridge local failure, resulting from sudden loss of a primary load carrying member.

2.2.1 Specific Local Resistance

The specific local resistance method requires that critical load carrying components are designed to withstand a specified level of threat, which may be in the form of blast, impact or fire loading. As a result, the structure is provided with additional strength at areas that are believed to be prone to accidental loads (e.g. exterior columns at risk from vehicular collision), or in key elements that are crucial to the overall structural stability. In the case of designing key elements, they should be able to develop their full resistance against an unanticipated load without failure of either the member itself or its connections. By activating the full resistance available in the key members, this approach maximizes their ability to deal with unforeseen hazards without having to redistribute loads.

One of the issues of designing to resist progressive collapse is that the loading events in question are outside the scope of normal design. Due to the unforeseen nature of these events, we cannot accurately predict their magnitude and location. Therefore, a threat-dependant design cannot guarantee that the building will perform adequately for events other than the one specifically considered [9].

2.2.2 Alternative Load Path Method

The alternative load path method was initially recommended following significant research during the 1970’s [10]. This design approach focuses on the behaviour of a structural system following the occurrence of an extreme event, and requires the structure to redistribute the loads following loss of a primary load bearing member. The basic procedure followed in any alternative path analysis involves removal of one, or several, primary structural components. The altered structure is then analysed to determine if the initiating damage propagates. This method promotes the use of regular structural configurations that exhibit ductility and energy absorption properties, which are desirable features for mitigating the risk of progressive collapse.

One of the main advantages of this technique is that it is a threat independent approach, and therefore, is valid for any hazard that may cause failure. This avoids one of the main difficulties faced by engineers in designing structures to resist progressive collapse; attempting to quantify an otherwise unknown loading event. The design guidelines produced by the Department of Defence [5] and the General Services Administration [6], in the United States, both recommend the use of this technique, and identify four alternative analytical approaches, of increasing complexity; linear static, nonlinear static, linear dynamic and nonlinear dynamic analysis.

Linear Static Analysis

The simplest form of the alternative load path method involves performing a linear static analysis on the damaged structure. This involves applying the fully factored gravity loads, in a single step, to the damaged structure. The proceeding analysis is based on the assumption of small deformations. Dynamic effects can be indirectly considered by assuming an equivalent static load based on a constant amplification factor, typically taken equal to 2.0 [5-6].

Nonlinear Static Analysis

Nonlinear static analysis improves on linear static analysis through inclusion of both geometric and material nonlinearities in the procedure. The inclusion of these nonlinearities is required to account for catenary/membrane effects, as well as to allow for accurate representation of inelastic response and the effects of the P-Δ effects.

Similar to the linear static approach, the nonlinear static approach applies a dynamic amplification factor, to account for time-dependant effects. However, the gravity loads are not applied in one step, but instead a vertical pushover analysis is employed. This involves incremental application of the loads until the maximum loads are attained or collapse occurs, and further improves the accuracy of the structural model.

Linear Dynamic Analysis

The sudden removal of a structural component results in an immediate change in the structural geometry. As a result of this, gravitational energy is released and the internal strain energy, and kinetic energy, of the structure can be expected to alter rapidly. Therefore dynamic effects are important when attempting to accurately represent the associated structural behaviour. Due to the localized nature of dynamic behavior, when using mode superposition all high modes of vibration should be included. As a result of this direct step-by-step integration methods are preferable, since such algorithms account for all possible vibration modes [11].

Linear dynamic analysis is unable to capture the nonlinear behaviour associated with collapse. Hence, although linear dynamic analysis is easier to apply than nonlinear dynamic analysis, this method requires extensive judgment on the part of the designer to establish whether P-Δ and membrane effects are significant and to determine whether the computed results are realistic.

Nonlinear Dynamic Analysis

The most rigorous approach for carrying out an alternative path analysis is through the use of nonlinear dynamic analysis. This method dynamically removes a member from the structure, which is then analysed taking account of both the geometric and material nonlinearities. This allows larger deformations and energy dissipation through material yielding, cracking and fracture [8]. More complex nonlinear dynamic analyses may also include dynamic effects, caused by the impact of failed members on the remaining structure [12].

It is important to emphasise that the analysis of a structure in a severely damaged state is a complex problem. The alternative path method is not intended to precisely model the progressive failure process. Instead, the purpose of the alternative path method is to assist engineers in designing more robust structures. Therefore, it is possible to use the simpler procedures but an experienced engineer with considerable knowledge and experience in structural modelling is essential to ensure validity of the results.

3. Modelling Progressive Collapse

As part of this research, a dynamic analysis program capable of following the sequence of failures that occur during a progressive collapse has been developed. This program implements the finite element method, and incorporates material nonlinearities through the formation of plastic hinges. Fig. 2 outlines the algorithm adopted for this purpose.

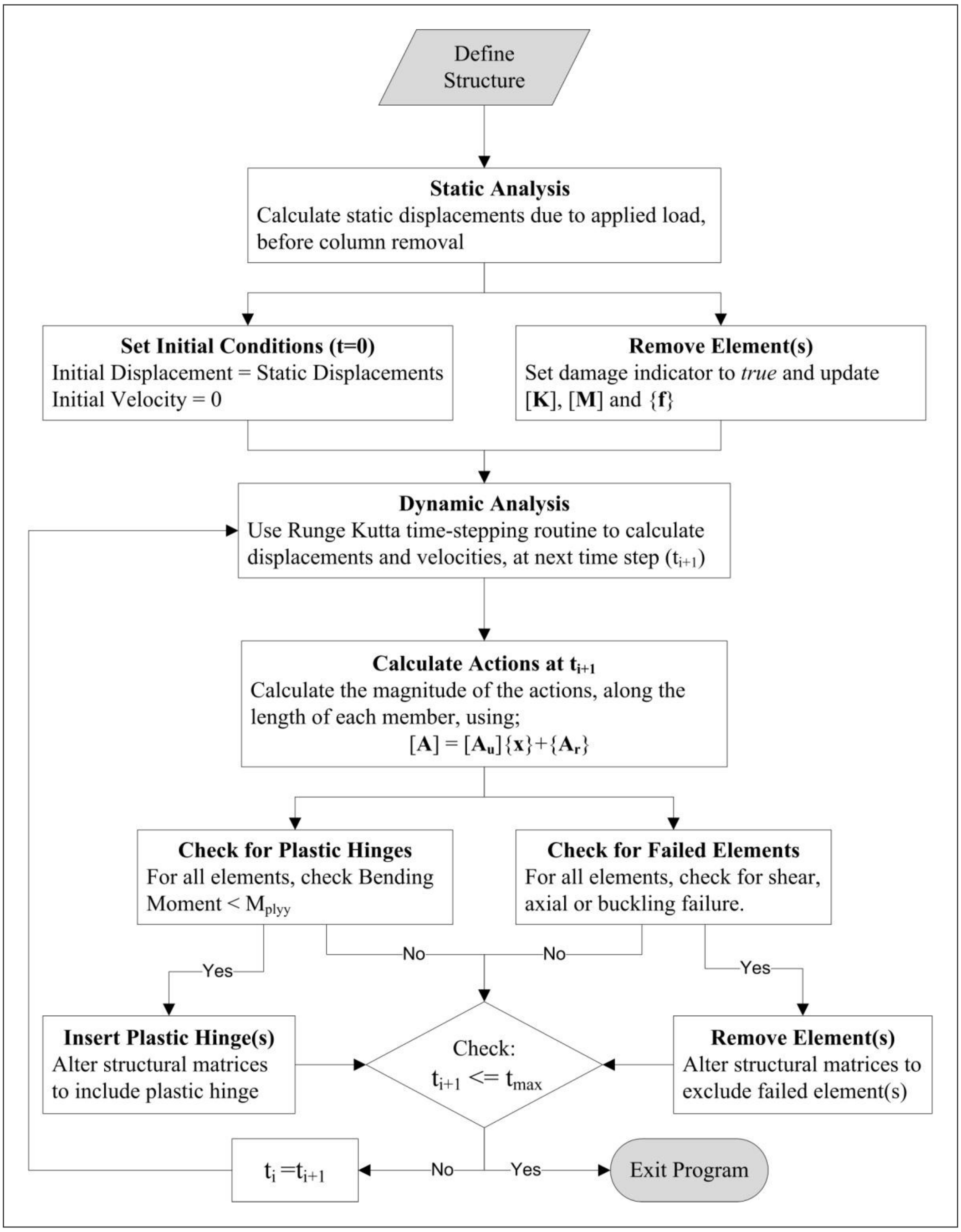

Fig. 2: Flowchart describing progressive collapse algorithm.

The algorithm implements a Runge-Kutta time-stepping routine to compute the structural response following the sudden removal of a structural member. The initial conditions for the structure are determined by calculating the static response of the structure to the unfactored design loads, prior to removal of the structural element. The initial displacements for the dynamic analysis are set equal to the static displacements and the initial velocities are set to zero. The algorithm then iterates through the time steps, calculating the displacements and velocities at each time step. The values of the structural actions along the length of each member are also computed, using appropriate shape functions. At each time step, the algorithm checks all members of the structure for plastic yielding or failure, and updates the stiffness and mass matrix, as well as the restraining force vector. At present, this program does not include the effects of structural damping.

4. Case Study: Progressive Collapse Analysis of 2D Frame

The following case study demonstrates the application of the progressive collapse program described in the preceding section. The behaviour of the two-storey frame shown in Fig. 3 is analysed following the removal of the central ground floor column. Local failure of this nature is consistent with that caused by a minor gas explosion or vehicular collision. However, collapse of this nature is usually initiated by unforeseen loading conditions. This presents the designer with the difficulty of attempting to quantify the extent of initial damage following an unknown event. For this reason, it is advisable that for a comprehensive progressive collapse analysis a wide range of initiating events should be considered, including the removal of multiple elements and the removal of elements at various locations throughout the structure.

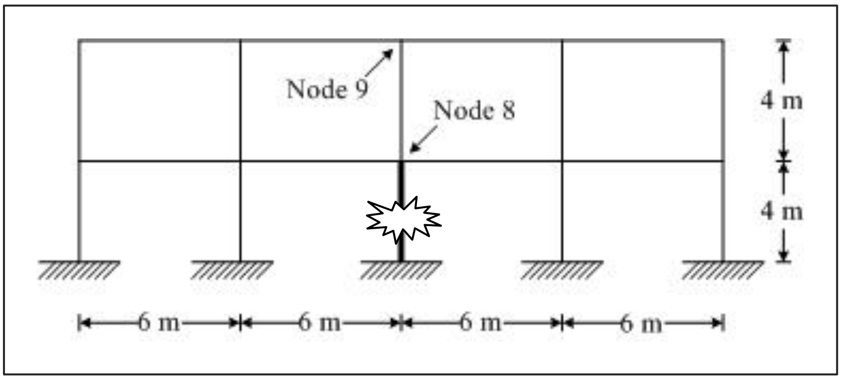

Fig. 3: Frame analysed using progressive collapse program.

This structure is designed to resist a uniformly distributed load, of magnitude 26,7 kN/m, across the entire floor area. Table 1 provides the capacities of the sections selected for this example.

Table 1: Capacities for the section sizes used in the analysis

Section Size	**f_y (MPa)**	**E (GPa)**	**L (m)**	**A (cm^2)**	**I (cm^4)**	**M_p (kNm)**	**N_c/N_t (kN)**	**V_c (kN)**
152x152x37 UC	275	210	4,0	47,1	2210	84,98	1295	226,1
305x102x28 UB	275	210	4,0	35,9	5370	110,8	987,3	315,2

The progressive collapse sequence is initiated by the instantaneous removal of the ground floor column (Fig. 4(a)). The time-stepping routine is applied at this point, allowing the loads to dynamically redistribute throughout the structure. Simultaneously, the structure is monitored for the formation of plastic hinges and unstable compression members. As time progresses, plastic hinges begin to form at the ends of the first and second floor beams, in the central two bays of the structure

(Fig. 4(b)). Following the formation of these hinges, significant bending occurs in the centre of the beams and additional plastic hinges form at nodes 8 and 9 (see Fig. 3). This results in the formation of unstable beam mechanisms and, therefore, the failure of the central two bays of the structure. Following this failure the forces continue to redistribute dynamically, however no further member failures occur.

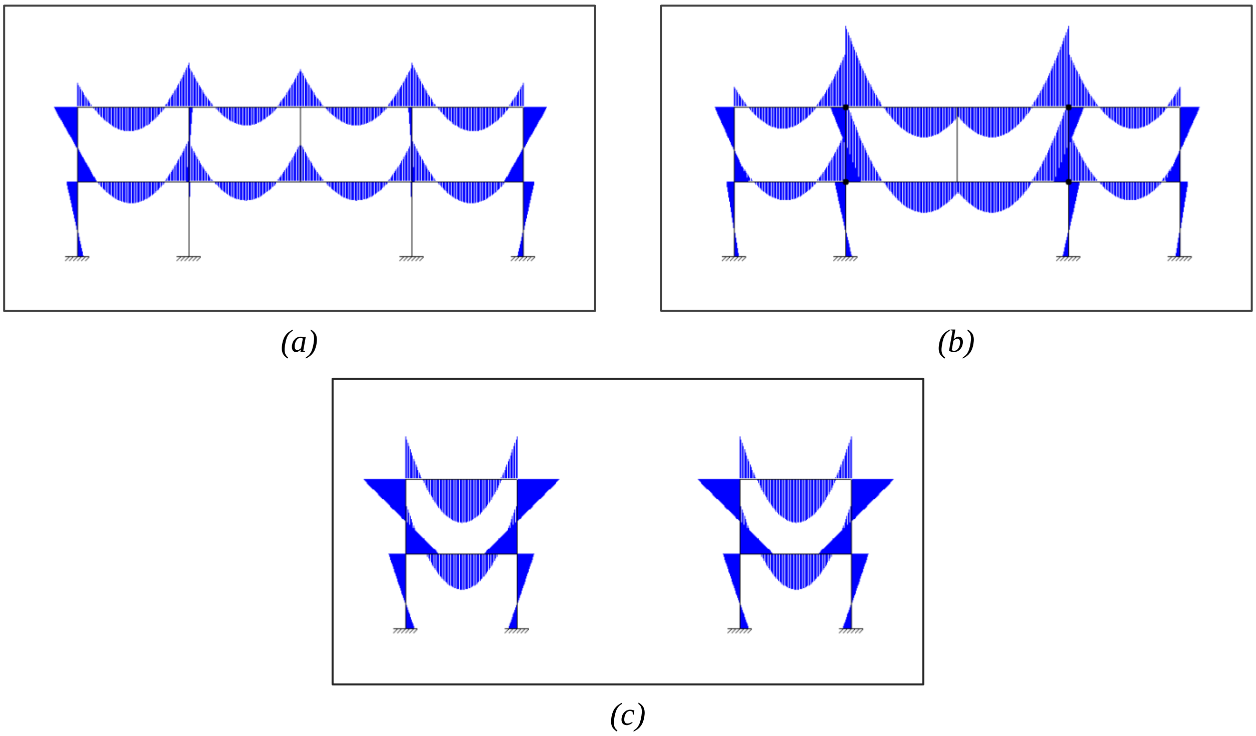

Fig. 4: Bending moment diagram (a) t = 0 ms, (b) t = 3 ms (first plastic hinges have formed) and (c) t =20 ms (beams have failed).

5. Discussion

By studying the images shown in Fig. 4, the range of bending moments experienced by the individual elements is clear. In particular, interior columns should be designed to withstand the increased bending moments associated with the loss of an adjacent bay. Also, the beam-column connections are subjected to large rotations during a collapse sequence and should be designed taking this into account.

6. Conclusions

This paper has presented a methodology to analyse the vulnerability of a structure to progressive collapse. The computer program developed can be used both as a design and an analysis tool, providing a simple method of assessing both existing and new buildings. The program allows the user to predict the extent of collapse following certain initiating events, and to identify vulnerable structural configurations. Software of this nature is a key tool for engineers when ensuring a structure possesses adequate excess capacity to resist the effects of unforeseen loading conditions.

This program is in the early stages of development, and there are a wide range of possible modifications for inclusion in future versions of the analysis program. At present, no load redistribution effects are considered following the failure of an element. However, in order to detect the propagation of failure due to load shedding, similar to that seen in the Ronan Point collapse, the effects of the impact of failed members on the floors below should be addressed. Also, the effects of geometric nonlinearities can be significant during progressive collapse, and hence the effects of moments caused by lateral displacements require some consideration.

7. Acknowledgements

This research is supported by the Irish Research Council for Science Engineering and Technology (IRCSET) Embark Initiative.

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