**Residual Axial Capacity of Reinforced Concrete Columns Subject to Internal Building Detonations**

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**Abstract**

This paper details the development of an engineering assessment procedure for reinforced concrete column failure when subjected to time-variant coupled axial and lateral loads due to internal building detonations. This is based on a comprehensive parametric study conducted using an advanced uncoupled Euler-Lagrange numerical modelling; splitting the structural and flow solvers for maximum integrity and accuracy. The column assessment charts discussed in this paper provide threshold combinations of TNT equivalence and stand-off distance for a range of column residual axial capacity levels corresponding to two key internal blast environments: vented and contained. This will be of direct relevance to both practitioners and researchers involved with protective design of civilian and military buildings.

**Keywords:** internal explosion; uplift force; damage assessment; dynamic response; blast; residual axial capacity

1. **Introduction**

Current research with respect to the protection of civilian infrastructure against complex blast loading conditions is primarily focused towards the effect of external explosive sources [[1](#_ENREF_1), [2](#_ENREF_2)]. As a consequence, the general literature on internal building detonations and specifically in the context of protective design and assessment of structures against these complex loading cases is inconclusive. In addition, existing assessment techniques developed for comparatively non-complex external explosive blast remain unconservative when applied to internal building detonations due to blast wave confinement and complex interaction with structural components. In particular, reinforced concrete (RC) columns in internal blast environments are subjected to time-variant uplift forces [[3-6](#_ENREF_3)] coupled with lateral pressures leading to destabilisation and a critical loss of structural integrity. The importance of these transient uplift forces on the response and structural adequacy of internal columns continues to be of topical importance to both practitioners and researchers.

Archive literature comprises research focused towards the extent of damage and residual axial capacity of RC columns subjected to coupled static axial compression forces and transient lateral loads due to external explosive blasts [[7-11](#_ENREF_7)]. Wu et al., [[9](#_ENREF_9)] conducted a series of high-fidelity numerical simulations of the transient-dynamic response of localised blast-damaged RC columns. This research led to a development of an analytical approach for estimating column residual axial capacity following external explosive blast conditions. Whilst majority of published research are focused towards comparatively large standoff external explosions, some provide results pertaining to the response behaviour of RC columns subjected to contact and extremely close-proximity detonation scenarios. Notable developments in this respect include the research conducted by Roller et al., [[8](#_ENREF_8)] and, Bao and Li [[11](#_ENREF_11)].

Although experimental blast trials always require privileged access and specialist facilities, in many cases costing prohibitive monetary sums, these tests have been of significant interest among many researchers. In an attempt to qualitatively and quantitatively investigate the ultimate failure mechanism and residual axial capacity of RC columns due to blast loading, Fujikake and Aemlaor [[7](#_ENREF_7)] conducted a series of experimental blast trials on a number of RC columns comprising excessive reinforcement ratios attributed to an earthquake resistant design approach. Importantly, these research outputs when applied to RC columns in internal blast environments can lead to unconservative predictions; as a result of transient uplift forces followed by large axial compression forces due to the rebounding effect of floor plates and cross girders. These blast-induced axial forces act as a strength degrading mechanism for primary structural members (columns) predominantly designed to resist static compression forces.

This research considers two key internal blast environments: vented and contained. In vented internal blast conditions, buildings are considered to comprise frangible perimeter walls and blast waves flow out rapidly, eventually reducing the net impulse acting on internal columns. Typical examples for this loading condition include explosions in areas such as: (i) – parking premises, (ii) open-plan floor areas with frangible facades and, (iii) – entrance lobby and overhanging areas. In contrast to the nature of vented blast conditions, contained explosions and consequential loading are characterised by extended pressure histories due to repetitive wave reflections occurring at

non-frangible building perimeter walls [[12](#_ENREF_12)]. In this research, separate sets of column damage assessment charts were developed for these two internal blast conditions. The interaction of blast waves with building partition walls was neglected in this research. The presence of strong partition walls can significantly influence the magnitude of blast and response behaviour of internal columns. In these conditions, loads acting on columns are initially transferred through partition walls, and blast pressures only act after breakage of the partition walls. As a direct consequence of this, internal columns tend to be subjected to significant bi-directional lateral loads causing a net torsional effect; however, this phenomenon is not of primary interest in this research.

This research employs the hydrocodes ‘Air3D’ [[13](#_ENREF_13)] and ‘Autodyn’ [[14](#_ENREF_14)] for conducting high-resolution computational fluid dynamics (CFD) simulations of internal blast actions, whilst Extreme Loading for Structures and the Applied Element Method ‘ELS’ [[15](#_ENREF_15)] is used for modelling the transient-dynamic structural response of columns. This is an uncoupled numerical technique in which large-deformation-induced pressure redistributions around columns are neglected in estimating transient load histories: blast wave interactions with structural components assumed to act as rigid targets. This is a reasonable approach and leads to conservative load estimations as demonstrated by Bφrvik et al., [[16](#_ENREF_16)]. Bφrvik et al., have shown that Lagrange uncoupled approaches, when compared with full-scale experimental test data, can significantly limit discrepancies between numerical predictions and corresponding test results in terms of the response of blast-loaded structural components.

The development of damage assessment charts was based on a comprehensive parametric study covering both contained and vented internal blast environments. The results of the parametric study were subsequently analysed using a non-linear multi-variable regression technique [[17](#_ENREF_17)] and presented in the form of assessment charts containing residual axial capacity levels against a number of input variables describing the blast scenario and column slenderness. Section 2 of the paper summarises a set of key outputs (previously published by the authors) pertaining to numerical modelling and verification. The parametric study is discussed in section 3, which is followed by section 4 containing the regression analysis outputs. Section 5 discusses the developed damage assessment charts. In section 6, conclusions are presented.

1. **Numerical modelling procedure**

The fundamental numerical modelling procedure and corresponding verification studies on the basis of published experimental test data were comprehensively described in a number of previous publications by the authors [[18-20](#_ENREF_18)]. This section summarises the key aspects pertaining to CFD simulation and transient-dynamic modelling of column response. Figure 1 illustrates the blast wave propagation and fluid-structure interaction due to a vented internal building detonation defined at 16kg of TNT equivalence detonated at a standoff of 3m from an internal column.

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**Figure 1**: Numerical modelling of complex flow fields due to internal blast actions.

With respect to modelling complex flow fields typical in confined blast environments, solution accuracy is significantly dependant on the fundamental modelling procedure and cell discretisation properties. Initial shock expansion stages involve with high pressures and temperatures, and contact discontinuities. As a consequence, flow fields within this region require a high resolution to accurately model the detonation process and behaviour of the expanding shock. This was

achieved by employing a material remapping technique, in which one-, two- and three-dimensional flow fields were independently modelled; with remapped data registries between different flow fields (see [18-20] for further details). Based on a number of sensitivity studies [[19](#_ENREF_19)], the cell size within one-, two- and three-dimensional scaled (1:25) flow fields was limited to 0.1mm radial, 1mm square and 2.5mm cubic respectively. A number of consequential pressure and impulse histories at different locations within a virtual building are shown in Figure 2(a)-2(b) [19]. In addition, Figure 2(c)-(d) shows the corresponding pressure and impulse histories due to a contained blast defined at 100kg of TNT equivalence detonated at a standoff of 2.83m.

**Figure 2:** Comparison of pressure (P) and impulse (I) histories [19]: (a) – vented blast, @0.75m on the internal column; (b) – vented blast, at the centre of the slab panel 1; (c) – contained blast, @0.75m on the internal column and; (d) – contained blast, at the centre of the slab panel 1.

Figure 3 illustrates an idealised AE structural model comprising four key components: core column, floor plates, cross girders and a virtual column connected to the top-end of the column. The virtual column defined the effect (axial stiffness) of upper floor members on column response using a modified Young’s modulus estimated from *(L×Ku) / A,* where *L* and *A* are the height and cross

sectional area of the virtual column and *Ku* is the elastic axial stiffness attributed to upper floor members, which was estimated from supplemental FE analyses [[21](#_ENREF_21)]. The fundamental numerical modelling technique, rate-dependent material properties and application of transient lateral and uplift loads to internal columns are not of primary interest in this paper. Interested readers on these aspects are directed to previous publications by the authors [18, 19]. Each numerical simulation comprised four evaluation stages: non-linear static analysis due to permanent loads, non-linear static analysis due to service loads, non-linear transient-dynamic analysis due to coupled axial and lateral blast loads and, static analysis due to an incremental axial load until the blast-damaged column fails in direct compression (estimation of column residual axial capacity).

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**Figure 3**: Numerical modelling of the transient-dynamic response of RC columns.

The AE numerical modelling procedure was compressively ratified and underwritten using a set of published experimental test data. Key characteristics considered in this respect were: (i) – qualitative parameters such as the characteristics of damage initiation and propagation, integrity of column reinforcement and ultimate failure mechanism and; (ii) – quantitative parameters including

column lateral deformation histories, longitudinal strains in reinforcement and support shear histories. The results of these verification studies are discussed in a number of previous publications by the authors [18, 19]. As an example, Figure 4 compares the failure mechanism numerically predicted for a column (356mm×356mm) subjected to a detonation of 584kg of TNT equivalence at a standoff of 3.96m with corresponding field and laboratory observations (see [19] for further details). With a high confidence towards the reliability and robustness of the numerical modelling procedure, the work was extended to conduct a comprehensive parametric study covering both vented and contained internal blast conditions. This paper is primarily focused towards the results of this parametric study and provides an advance on the previous publications by the authors.

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**Figure 4**: Qualitative verification of column response modelling [19].

1. **Parametric study**

The parametric study comprised 300 independent numerical simulations for each internal blast condition. In these numerical simulations, the extent of column damage was described, both qualitatively and quantitatively, using two output parameters (η and α) defined against four key input variable categories: blast scenario, column slenderness, reinforcement ratios and material properties. These input variables are provided in Table 1. Tensile strength (*fct)*, Young’s modulus (*Ec*) and shear modulus (*Gc*) of concrete were not independently considered because of the direct dependency of these parameters on compressive strength of concrete (*fck*). Similarly, yield strength of steel was set to a constant value (*fy* = 460MPa) leading to modifications of the total longitudinal reinforcement area at different yield strength values.

|  |  |  |
| --- | --- | --- |
| Variable group | Input variable | Remarks |
| Column slenderness, λ | Width, B | *= 460MPa*  *Sv - Link spacing*  *deff - Effective depth*  *Ec, Gc and ft = ƒ( fck)* |
| Depth, D |
| Height, H |
| Blast scenario | TNT Equivalence, M |
| Standoff distance, R |
| Reinforcement details | ρl |
| ρt |
| Material properties | Design compressive strength of concrete, *fck* |

**Table 1**: Independent variables for the parametric study.

The output parameter η (damage index) describes the extent of overall column damage in a qualitative manner based on key observations such as damage progression, extent of localised spallation, integrity of reinforcement arrangement and ultimate failure mechanism. The output parameter α is the column residual axial capacity index defined as Nd / Nud, where Nd and Nud are the column axial compression capacity in damaged and undamaged conditions respectively. The undelaying numerical procedure adopted for estimating α is illustrated in Figure 5. This involves with incrementally applying a static axial load to each blast-damaged column until the column fails in direct compression. These incremental axial loads were applied to the virtual column (see Figure 3). In order to permit a proper axial load transferral to the column, vertical constraints at the top of the virtual column were removed and all springs were set to a significantly higher stiffness to minimise localised axial deformations within the virtual column.

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**Figure 5**: Estimation of column residual axial capacity following internal blast actions.

Overall, based on the extent of column damage and estimated column residual axial capacity in each analysis case, it was possible to define a damage classification system comprising five damage classes. This is provided in Table 2, together with the ranges of η and α corresponding to each damage class.

|  |  |  |  |
| --- | --- | --- | --- |
| Damage class | η | α | Remarks |
| None  (ND) | 1≤ η<4 | 1.0 | By inspection:  No visible cracks and localised concrete damage, reinforcement intact, no large lateral deformations and full residual axial capacity |
| Light  (LD) | 4≤ η<8 | <1.0 &  ≥0.92 | By inspection:  Minor to moderate flexural and diagonal shear cracks, but no localised concrete damage, reinforcement intact, no large lateral deformations, almost full residual axial capacity |
| Moderate  (MD) | 8≤ η<16 | <0.92 &  ≥0.63 | By inspection:  Moderate flexural and diagonal shear cracks with localised concrete spallation to a certain extent, reinforcement intact, no large lateral deformations, moderate residual axial capacity |
| Severe  (SSD) | 16≤ η<32 | <0.63 &  ≥0.13 | By inspection:  Severe concrete cracking and spallation with direct shear phenomenon, main reinforcement intact, ruptured stirrups, large lateral deformations, low residual axial capacity |
| Imminent collapse (SSD\*) | η≥32 | =0 | By inspection:  Column severely damaged and collapsed (blown off or total compression failure), zero residual axial capacity |

**Table 2:** Damage classification system developed as part of this research.

Figure 6 shows a group of numerical modelling outputs categorised according to the defined damage classification system. Figure 6 also contains a set of charts highlighting the relationship between α and η for each damage class. The data points shown in these charts were obtained from the results of the parametric study analyses. Tables 3 and 4 provide part of the parametric study outputs for vented and contained blast conditions respectively.

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**Figure 6**: Damage classification system comprising the ranges of α and η for each damage level.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No. | B  (mm) | D  (mm) | H  (m) | M  (kg) | R  (m) | Z  (m/kg1/3) | ρl | Astdfy/s  (kN) | Parametric study outputs | | | | | | | | | | | | | | |
| η | | | | | α | | | | | Damage class | | | | |
| *fck*=  30 | 40 | 50 | 60 | 100 | *fck*=  30 | 40 | 50 | 60 | 100 | *fck*=  30 | 40 | 50 | 60 | 100 |
| 1 | 400 | 400 | 3.0 | 40 | 2 | 0.58 | 4 | 165.7 | 5.00 | 5.00 | 4.00 | 3.5 | 2.0 | 0.94 | 0.95 | 0.97 | 1.00 | 1.00 | 2 | 2 | 2 | 1 | 1 |
| 2 | 350 | 400 | 4.0 | 200 | 4 | 0.68 | 6 | 123.4 | 10.0 | 8.00 | 6.00 | 5.5 | 3.2 | 0.75 | 0.90 | 0.93 | 0.94 | 1.00 | 3 | 3 | 2 | 2 | 1 |
| 3 | 400 | 300 | 3.2 | 120 | 4 | 0.81 | 3 | 89.6 | 12.0 | 10.0 | 8.00 | 6 | 4.0 | 0.70 | 0.76 | 0.91 | 0.94 | 0.99 | 3 | 3 | 3 | 2 | 2 |
| 4 | 350 | 400 | 4.0 | 80 | 3 | 0.70 | 3 | 100.3 | 4.50 | 4.00 | 3.50 | 3 | 1.5 | 0.94 | 0.96 | 1.00 | 1.00 | 1.00 | 2 | 2 | 1 | 1 | 1 |
| 5 | 350 | 300 | 3.5 | 5 | 2.5 | 1.46 | 4 | 119 | 2.50 | 2.00 | 1.50 | 1 | 0.2 | 1.0 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 6 | 400 | 350 | 3.2 | 136 | 1.8 | 0.35 | 6 | 140.5 | 50.0 | 45.0 | 40.0 | 35 | 32 | 0.0 | 0.00 | 0.00 | 0.00 | 0.04 | 5 | 5 | 5 | 5 | 5 |
| 7 | 400 | 400 | 3.0 | 79 | 3 | 0.70 | 5 | 123.6 | 7.00 | 6.00 | 4.00 | 3 | 1.0 | 0.92 | 0.94 | 0.98 | 1.00 | 1.00 | 2 | 2 | 2 | 1 | 1 |
| 8 | 400 | 300 | 3.5 | 22 | 2.8 | 1.00 | 6 | 117 | 4.00 | 3.00 | 2.00 | 1 | 0.1 | 0.97 | 1.00 | 0.00 | 1.00 | 1.00 | 2 | 2 | 1 | 1 | 1 |
| 9 | 300 | 300 | 3.5 | 248 | 2.2 | 0.35 | 6 | 177.2 | 65.0 | 60.0 | 56.0 | 52 | 46 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 10 | 350 | 400 | 4.0 | 244 | 2.5 | 0.40 | 4 | 166.2 | 40.0 | 40.0 | 37.0 | 35 | 31 | 0.0 | 0.00 | 0.00 | 0.08 | 0.02 | 5 | 5 | 5 | 5 | 4 |
| 11 | 400 | 300 | 3.0 | 296 | 4 | 0.60 | 6 | 87.8 | 26.0 | 24.0 | 22.0 | 22 | 18 | 0.35 | 0.30 | 0.34 | 0.34 | 0.42 | 4 | 4 | 4 | 4 | 4 |
| 12 | 300 | 350 | 3.2 | 2 | 2.2 | 1.70 | 5 | 142.3 | 1.50 | 1.50 | 1.00 | 0.5 | 0.0 | 1.0 | 1.00 | 0.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 13 | 400 | 300 | 4.0 | 200 | 3.8 | 0.65 | 6 | 87.8 | 20.0 | 17.0 | 14.0 | 12 | 8.0 | 0.29 | 0.45 | 0.66 | 0.72 | 0.85 | 4 | 4 | 3 | 3 | 3 |
| 14 | 250 | 350 | 3.2 | 117 | 2.2 | 0.45 | 4 | 107.7 | 24.0 | 20.0 | 16.0 | 14 | 9.0 | 0.26 | 0.39 | 0.62 | 0.68 | 0.79 | 4 | 4 | 4 | 3 | 3 |
| 15 | 250 | 300 | 3.0 | 50 | 2.4 | 0.65 | 4 | 119.9 | 6.00 | 5.00 | 4.00 | 2 | 0.4 | 0.95 | 0.96 | 0.97 | 1.00 | 1.00 | 2 | 2 | 2 | 1 | 1 |
| 16 | 350 | 300 | 3.5 | 296 | 2 | 0.30 | 4 | 119 | 80.0 | 75.0 | 69.0 | 66 | 60 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 17 | 300 | 350 | 3.0 | 125 | 3 | 0.60 | 6 | 106.2 | 18.0 | 15.0 | 11.0 | 9 | 5.0 | 0.46 | 0.64 | 0.74 | 0.81 | 0.95 | 4 | 3 | 3 | 3 | 2 |
| 18 | 300 | 250 | 4.0 | 19 | 4 | 1.50 | 3 | 144.9 | 2.00 | 2.00 | 1.50 | 0.6 | 0.0 | 1.0 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 19 | 250 | 300 | 3.2 | 187 | 2 | 0.35 | 3 | 120.6 | 60.0 | 55.0 | 51.0 | 50 | 45 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 20 | 300 | 250 | 3.0 | 85 | 2.2 | 0.50 | 5 | 95.2 | 22.0 | 20.0 | 19.0 | 15 | 10 | 0.26 | 0.38 | 0.41 | 0.64 | 0.77 | 4 | 4 | 4 | 3 | 3 |
| 21 | 400 | 350 | 3.2 | 3 | 3 | 2.00 | 3 | 85.8 | 1.00 | 1.00 | 0.50 | 0.5 | 0.1 | 1.0 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 22 | 250 | 250 | 3.0 | 296 | 3 | 0.45 | 5 | 143.6 | 80.0 | 70.0 | 65.0 | 62 | 54 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 23 | 300 | 300 | 3.2 | 25 | 3.5 | 1.20 | 5 | 89 | 3.00 | 2.50 | 1.80 | 0.5 | 0.0 | 1.0 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 24 | 300 | 250 | 3.2 | 258 | 3.5 | 0.55 | 6 | 94.7 | 50.0 | 45.0 | 39.0 | 37 | 33 | 0.0 | 0.00 | 0.00 | 0.03 | 0.04 | 5 | 5 | 5 | 5 | 5 |
| 25 | 350 | 250 | 3.0 | 296 | 2 | 0.30 | 6 | 141.2 | 65.0 | 60.0 | 54.0 | 50 | 45 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 26 | 250 | 300 | 3.5 | 3 | 2.2 | 1.50 | 4 | 89.9 | 2.00 | 2.00 | 1.00 | 0.5 | 0.0 | 1.0 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 27 | 350 | 250 | 3.5 | 53 | 3 | 0.80 | 5 | 94.8 | 6.50 | 5.00 | 4.00 | 3 | 1.5 | 0.93 | 0.94 | 1.00 | 1.00 | 1.00 | 2 | 2 | 2 | 1 | 1 |
| 28 | 400 | 400 | 4.0 | 102 | 2.8 | 0.60 | 5 | 98.8 | 7.50 | 7.00 | 6.00 | 4 | 2.0 | 0.92 | 0.91 | 0.94 | 0.98 | 1.00 | 2 | 2 | 2 | 2 | 1 |
| 29 | 350 | 350 | 3.0 | 145 | 2.1 | 0.40 | 4 | 85.5 | 38.0 | 34.0 | 31.0 | 28 | 25 | 0.0 | 0.00 | 0.12 | 0.21 | 0.28 | 5 | 5 | 4 | 4 | 4 |
| 30 | 350 | 300 | 4.0 | 216 | 3 | 0.50 | 3 | 89.8 | 45.0 | 40.0 | 36.0 | 34 | 29 | 0.0 | 0.00 | 0.00 | 0.05 | 0.16 | 5 | 5 | 5 | 5 | 4 |

**Table 3**: Part of the parametric study data set: vented blast scenario.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No. | B  (mm) | D  (mm) | H  (m) | M  (kg) | R  (m) | Z  (m/kg1/3) | ρl | Astdfy/s  (kN) | Parametric study outputs | | | | | | | | | | | | | | |
| η | | | | | α | | | | | Damage class | | | | |
| *fck*=  30 | 40 | 50 | 60 | 100 | *fck*=  30 | 40 | 50 | 60 | 100 | *fck*=  30 | 40 | 50 | 60 | 100 |
| 1 | 400 | 400 | 3.0 | 40 | 2 | 0.58 | 4 | 165.7 | 8.0 | 8.0 | 7.0 | 6 | 4 | 0.90 | 0.91 | 0.90 | 0.94 | 0.95 | 3 | 3 | 2 | 2 | 2 |
| 2 | 350 | 400 | 4.0 | 102 | 3.2 | 0.68 | 6 | 123.4 | 11 | 8.0 | 7.0 | 6 | 4 | 0.74 | 0.86 | 0.90 | 0.94 | 0.96 | 3 | 3 | 2 | 2 | 2 |
| 3 | 400 | 300 | 3.2 | 29 | 2.5 | 0.81 | 3 | 89.6 | 9.0 | 6.5 | 6.0 | 5 | 3 | 0.81 | 0.92 | 0.94 | 0.96 | 0.96 | 3 | 2 | 2 | 2 | 1 |
| 4 | 350 | 400 | 4.0 | 80 | 2 | 0.46 | 3 | 100.3 | 13 | 12 | 12 | 11 | 6 | 0.69 | 0.72 | 0.72 | 0.89 | 0.93 | 3 | 3 | 3 | 3 | 2 |
| 5 | 350 | 300 | 3.5 | 5 | 2.5 | 1.46 | 4 | 119 | 2.5 | 2.0 | 1.5 | 1.2 | 0.3 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 6 | 400 | 350 | 3.2 | 136 | 1.8 | 0.35 | 6 | 140.5 | 54 | 49 | 48 | 44 | 37 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 5 | 5 | 5 | 5 | 5 |
| 7 | 400 | 400 | 3.0 | 79 | 3 | 0.70 | 5 | 123.6 | 9.0 | 9.0 | 7.0 | 5.5 | 3 | 0.82 | 0.79 | 0.92 | 0.96 | 0.99 | 3 | 3 | 2 | 2 | 1 |
| 8 | 400 | 300 | 3.5 | 22 | 2.8 | 1.00 | 6 | 117 | 6.0 | 6.0 | 5.0 | 4 | 2 | 0.92 | 0.93 | 0.95 | 0.96 | 1.00 | 2 | 2 | 2 | 2 | 1 |
| 9 | 300 | 300 | 3.5 | 248 | 2.2 | 0.35 | 6 | 177.2 | 70 | 65 | 61 | 58 | 50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 10 | 350 | 400 | 4.0 | 200 | 2.5 | 0.43 | 4 | 166.2 | 43 | 42 | 38 | 37 | 33 | 0.00 | 0.00 | 0.03 | 0.05 | 0.08 | 5 | 5 | 5 | 5 | 5 |
| 11 | 400 | 300 | 3.0 | 138 | 3.1 | 0.60 | 6 | 87.8 | 28 | 27 | 26 | 25 | 20.5 | 0.21 | 0.21 | 0.26 | 0.28 | 0.39 | 4 | 4 | 4 | 4 | 4 |
| 12 | 300 | 350 | 3.2 | 2 | 2.2 | 1.70 | 5 | 142.3 | 1.5 | 1.5 | 1.5 | 1 | 0.2 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 13 | 400 | 300 | 4.0 | 119 | 3.2 | 0.65 | 6 | 87.8 | 24 | 21 | 19 | 18 | 15 | 0.30 | 0.35 | 0.40 | 0.43 | 0.39 | 4 | 4 | 4 | 4 | 3 |
| 14 | 250 | 350 | 3.2 | 117 | 2.2 | 0.45 | 4 | 107.7 | 30 | 28 | 25 | 24 | 17 | 0.16 | 0.22 | 0.26 | 0.30 | 0.37 | 4 | 4 | 4 | 4 | 4 |
| 15 | 250 | 300 | 3.0 | 50 | 2.4 | 0.65 | 4 | 119.9 | 10 | 8.0 | 7.0 | 6 | 3 | 0.77 | 0.89 | 0.92 | 0.92 | 0.02 | 3 | 3 | 2 | 2 | 1 |
| 16 | 350 | 300 | 3.5 | 296 | 2 | 0.30 | 4 | 119 | 90 | 85 | 81 | 77 | 71 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 17 | 300 | 350 | 3.0 | 125 | 3 | 0.60 | 6 | 106.2 | 23 | 21 | 18 | 16 | 11 | 0.31 | 0.37 | 0.43 | 0.58 | 0.65 | 4 | 4 | 4 | 4 | 3 |
| 18 | 300 | 250 | 4.0 | 13 | 3.5 | 1.50 | 3 | 144.9 | 2.0 | 2.0 | 2.0 | 1.5 | 0.3 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 19 | 250 | 300 | 3.2 | 187 | 2 | 0.35 | 3 | 120.6 | 67 | 63 | 60 | 57 | 49 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 20 | 300 | 250 | 3.0 | 85 | 2.2 | 0.50 | 5 | 95.2 | 27 | 25 | 23 | 20 | 16 | 0.23 | 0.28 | 0.32 | 0.37 | 0.43 | 4 | 4 | 4 | 4 | 4 |
| 21 | 400 | 350 | 3.2 | 3 | 3 | 2.00 | 3 | 85.8 | 1.0 | 1.0 | 0.6 | 0.5 | 0.2 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 22 | 250 | 250 | 3.0 | 296 | 3 | 0.45 | 5 | 143.6 | 95 | 86 | 82 | 76 | 67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 23 | 300 | 300 | 3.2 | 25 | 3.5 | 1.20 | 5 | 89 | 6.0 | 4.0 | 3.0 | 2.5 | 1.2 | 0.95 | 0.96 | 1.00 | 1.00 | 1.00 | 2 | 2 | 1 | 1 | 1 |
| 24 | 300 | 250 | 3.2 | 132 | 2.8 | 0.55 | 6 | 94.7 | 55 | 50 | 46 | 43 | 39 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 5 | 5 | 5 | 5 | 5 |
| 25 | 350 | 250 | 3.0 | 296 | 2 | 0.30 | 6 | 141.2 | 70 | 65 | 61 | 57 | 51 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |
| 26 | 250 | 300 | 3.5 | 3 | 2.2 | 1.50 | 4 | 89.9 | 2.0 | 2.0 | 1.5 | 1 | 0.5 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | 1 | 1 | 1 | 1 |
| 27 | 350 | 250 | 3.5 | 53 | 3 | 0.80 | 5 | 94.8 | 9.0 | 7.0 | 5.0 | 4 | 1.5 | 0.86 | 0.93 | 0.95 | 0.98 | 1.00 | 3 | 2 | 2 | 2 | 1 |
| 28 | 400 | 400 | 4.0 | 150 | 2.8 | 0.53 | 5 | 98.8 | 12 | 11 | 9.0 | 8 | 5 | 0.70 | 0.76 | 0.88 | 0.91 | 0.94 | 3 | 3 | 3 | 3 | 2 |
| 29 | 350 | 350 | 3.0 | 145 | 2.1 | 0.40 | 4 | 85.5 | 42 | 39 | 35 | 33 | 29 | 0.00 | 0.02 | 0.03 | 0.05 | 0.11 | 5 | 5 | 5 | 5 | 4 |
| 30 | 350 | 300 | 4.0 | 216 | 3 | 0.50 | 3 | 89.8 | 55 | 50 | 47 | 45 | 41 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5 | 5 | 5 | 5 | 5 |

**Table 4:** Part of the parametric study data set: contained blast scenario.

1. **Assessment chart development**

The development of assessment charts for column residual axial capacity was based on a multi-variable non-linear regression analysis technique with Chi-Square minimisation (see [[17](#_ENREF_17)] for further details). In this method, the first step involved with relating the output variables η and α to the independent parameters using a global non-linear regression. This is described as:

|  |  |
| --- | --- |
|  | (1) |

Functions *f1,* *f2, f3, f4, f5*, *f6* and*f7* are secondary non-linear regressions describing the relationship between the output variables and each independent parameter. These functions were defined using a set of independent curve fitting analyses in which each input variable was separately considered with constant values assigned to the rest of the independent parameters [[21](#_ENREF_21)]. The effect of column slenderness parameters (B, D and H) on α and η was shown to have polynomial relationships, whilst those corresponding to the rest of the input variables were power functions. Substituting these secondary functions to Equation 1, the global regression function is written as:

|  |  |
| --- | --- |
|  | (2) |

Parameters and *t* are model constants and were derived from iterative Chi-Square minimisation analyses. In these analyses, the general non-linear model was expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

where, *η* represents the data to be modelled, are independent variables, are the model parameters and *ε* are the residuals. Numerical iterations were performed until deviation of theoretical data with respect to actual data is minimised (fit converged); a chi-square (*χ2*) minimisation technique with χ2 defined as:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

where, is the row vector for the ith (i = 1, 2, 3,.., n) observation. The vector is estimated using the normal equations which are set to be zero for the partial derivatives of *χ2* with respect to each as given below:

|  |  |
| --- | --- |
|  | (5) |

Table 5 provides the outputs of curve fitting analyses corresponding to vented internal blast scenarios.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Group | Name | Compressive strength class (in MPa) | | | | |
| 30 | 40 | 50 | 60 | 100 |
| Iterations performed | 127 | 74 | 78 | 81 | 70 |
| Reduced Chi-Square | 1.9251559 | 2.404868 | 2.0060476 | 2.3059571 | 2.4538795 |
| Residual Sum of Squares | 117.8773383 | 95.8827557 | 88.1028099 | 75.2012714 | 77.7159514 |
| R2 | 0.9372380 | 0.9393929 | 0.9353521 | 0.9403742 | 0.9272219 |
| Adjusted R2 | 0.8986602 | 0.8966115 | 0.8997183 | 0.8982855 | 0.8958492 |
| Model  constants | a | -0.0027034 | 0.0250224 | 0.0300554 | 1.14078E-04 | 8.52191E-04 |
| b | -4809.7856333 | 34606.243 | -5592.0664 | 66840.699 | 10121.811 |
| c | 20.3059469 | -140.30345 | 22.689745 | -280.64972 | -42.455193 |
| d | -0.0263901 | 0.1793915 | -0.0285682 | 0.3535269 | 0.0533838 |
| e | -2697.3805 | 104.87879 | 4926.6768 | 87.755351 | 2605.8455 |
| f | -7.7988301 | 0.1081912 | 24.380551 | 61.929088 | 63.085921 |
| g | 0.0218044 | -4.1443E-04 | -0.0549164 | -0.1118801 | -0.1124766 |
| h | 0.196467 | 0.1858859 | -0.0091184 | 0.0652517 | 0.1924716 |
| i | -0.1507623 | -0.1296631 | 0.0064484 | -0.0482367 | -0.1282258 |
| j | 0.0202397 | 0.0178985 | -8.8242E-04 | 0.0064893 | 0.0180131 |
| k | -0.0389629 | 0.0629224 | -0.0221215 | -0.341185 | -0.3780179 |
| l | -0.0467886 | 0.0230512 | 0.0204891 | 0.0220761 | 0.0053562 |
| m | 1.0953723 | 1.1485806 | 1.2098642 | 1.3405557 | 1.4359031 |
| n | -0.0017605 | -0.0017605 | -0.0017605 | -0.0017605 | -0.0017605 |
| o | -0.0133501 | -0.0133501 | -0.0133501 | -0.0133501 | -0.0133501 |
| p | 1.2403102 | 1.2403102 | 1.2403102 | 1.2403102 | 1.2403102 |
| q | 0.1779412 | 0.1779412 | 0.1779412 | 0.1779412 | 0.1779412 |
| r | 0.9913254 | 0.9913254 | 0.9913254 | 0.9913254 | 0.9913254 |
| s | 2.0705667 | 2.0705667 | 2.0705667 | 2.0705667 | 2.0705667 |
| t | 4.2875545 | 4.2875545 | 4.2875545 | 4.2875545 | 4.2875545 |

**Table 5:** Curve fitting analysis outputs: vented blast condition.

The estimated coefficient of determination (R2), reduced Chi-Square and residual sum of squares indicate a good correlation between the predicted and actual data sets. Importantly, despite the high level of fitting accuracy, scatter plots of the predicted outputs (ηp) versus actual data (ηa) (see

Figures 7 and 8) indicate that the regression analyses do not always lead to safe-conservative predictions; due to regular underestimations of the output variables. This is an important characteristic typically exhibited in multi-variable curve fitting analyses; however, the extent of these underestimations can be effectively minimised using a correction factor. The derivation of these correction factors (ϕ= ηa/ηp) for vented and contained blast conditions is illustrated in Figures 7 and 8 respectively. Based on the scatter plots shown in Figures 7 and 8, ϕ was considered to be 1.25 for both blast conditions, and output values predicted from the non-linear regressions were multiplied by 1.25 to estimate the corresponding actual output variables required for safe-conservative vulnerability assessments of internal columns.

**Figure 7:** Correction factor ϕ for vented internal blast conditions.

**Figure 8:** Correction factor ϕ for contained internal blast conditions

1. **Assessment charts for column residual axial capacity**

The non-linear multi-variable regressions derived in Section 4 were subsequently used to develop a set of assessment charts for column residual axial capacity. These assessment charts provide threshold combinations of TNT equivalency and standoff distance corresponding to different residual axial capacity levels based on column slenderness, reinforcement ratios and design compressive strength of concrete. Table 6 provides the complete set of internal blast scenarios utilised for developing the assessment charts.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | Figure  Tag | *fck*(MPa) | Column dimensions | | | | Main reinforcement | | | Stirrups | | | |
| B  (m) | D  (m) | H  (m) | Cover  (mm) | Φ  (mm) | n | *fyk*  (MPa) | ϕ  (mm) | *fyk*  (MPa) | *Sv*  (mm) | deff  (mm) |
| **A)**  Effect of  concrete  strength  (*fck*) | A-1 | 30 | 300 | 300 | 3.5 | 30 | 32 | 8 | 460 | 10 | 460 | 120 | 233 |
| A-2 | 40 | 300 | 300 | 3.5 | 30 | 32 | 8 | 460 | 10 | 460 | 120 | 233 |
| A-3 | 50 | 300 | 300 | 3.5 | 30 | 32 | 8 | 460 | 10 | 460 | 120 | 233 |
| A-4 | 60 | 300 | 300 | 3.5 | 30 | 32 | 8 | 460 | 10 | 460 | 120 | 233 |
| A-5 | 100 | 300 | 300 | 3.5 | 30 | 32 | 8 | 460 | 10 | 460 | 120 | 233 |
| **B)**  Column  orientation  (B×D) | B-1 | 30 | 250 | 300 | 3.0 | 30 | 32 | 8 | 460 | 10 | 460 | 100 | 233 |
| B-2 | 30 | 300 | 250 | 3.0 | 30 | 32 | 8 | 460 | 10 | 460 | 100 | 183 |
| B-3 | 30 | 300 | 400 | 3.0 | 30 | 32 | 8 | 460 | 10 | 460 | 100 | 333 |
| B-4 | 30 | 400 | 300 | 3.0 | 30 | 32 | 8 | 460 | 10 | 460 | 100 | 233 |
| B-5 | 30 | 350 | 450 | 3.0 | 30 | 32 | 8 | 460 | 10 | 460 | 100 | 383 |
| B-6 | 30 | 450 | 350 | 3.0 | 30 | 32 | 8 | 460 | 10 | 460 | 100 | 283 |
| **C)**  Column  Height  (H) | C-1 | 30 | 300 | 350 | 3.0 | 25 | 25 | 8 | 460 | 10 | 460 | 150 | 295 |
| C-2 | 30 | 300 | 350 | 3.2 | 25 | 25 | 8 | 460 | 10 | 460 | 150 | 295 |
| C-3 | 30 | 300 | 350 | 3.5 | 25 | 25 | 8 | 460 | 10 | 460 | 150 | 295 |
| C-4 | 30 | 300 | 350 | 3.8 | 25 | 25 | 8 | 460 | 10 | 460 | 150 | 295 |
| C-5 | 30 | 300 | 350 | 4.0 | 25 | 25 | 8 | 460 | 10 | 460 | 150 | 295 |

**Table 6**: Damage assessment scenarios considered for developing the column residual axial capacity charts.

Each assessment chart presented in this section is labelled using the corresponding figure-tag provided in Table 6. For any specific set of column dimensions, design compressive strength of concrete and reinforcement ratios, it is possible to construct a similar assessment chart using the non-linear regressions developed for vented and contained internal blast conditions.

Figures 9 and 10 show the assessment charts corresponding to different design compressive strengths of concrete; for vented and contained internal blast conditions respectively. In each chart, four threshold residual axial capacity levels are provided. These threshold lines are labelled based on the minimum residual axial capacity level corresponding to each damage level. For a particular assessment case, all M and R combinations below the threshold line ‘0 (=α)’ and in between the threshold lines ‘0’ and ‘0.63’ describe an imminent column failure (SSD\*) and a severe structural damage (SSD) leading to a significant loss of column residual axial capacity respectively. In these cases, the building should be designed to comprise alternative means of redistributing service loads to avoid catastrophic progressive failures. All blast scenarios in between the threshold lines ‘0.63’ and ‘0.92’ describe a moderate column damage as described in Table 2. Damage levels corresponding to the regions in between the threshold lines ‘0.92’ and ‘1.0’, and below the threshold line ‘1.0’ describe a low damage and no damage scenarios respectively.

**Figure 9:** Column residual axial capacity versus compressive strength of concrete: vented blast condition

**Figure10:** Column residual axial capacity versus compressive strength of concrete: contained blast condition.

It is evident from the assessment charts shown in Figures 9 and 10 that design compressive strength of concrete can noticeably influence the extent of column damage. Increasing compressive strength from 30MPa, through 40MPa, 50MPa and 60MPa, to 100MPa reduced the vulnerability of columns to all damage classes due to both vented and contained internal blast conditions. In addition, compared to vented internal blast conditions, contained blasts caused more damage and led to reduced residual axial capacity levels in columns; due to repetitive reflections and significant confinement of blast waves. This is evident from the assessment charts shown in Figures 9 and 10 for vented and contained blast conditions respectively.

The orientation of rectangular columns with respect to the direction of blast waves can influence the overall damage behaviour of columns due to: (i) – change in overall lateral stiffness and, (ii) – change in the projected column area to the blast influencing the magnitude of consequential pressure loads. The assessment charts shown in Figures 11 (B-2, B-4 and B-6) and 12(B-2, B-4 and B-6) correspond with columns responding and deforming about the weaker axis (D<B). Subsequently, the columns were rotated by 90 degrees (D>B) to permit them to deform about the stronger axis. The corresponding assessment charts are shown in Figures 11 (B-1, B-3 and B-5) and 12(B-1, B-3 and B-5) respectively for vented and contained internal blast conditions. This change in column orientation noticeably reduced the column vulnerability to an imminent collapse. This is because, complete structural failure of a column, characterised with ruptured longitudinal reinforcement occurring at large blast magnitudes, is significantly dependant on column overall stiffness and strength partially governed by the bending axis of rectangular columns. In contrast to this behaviour, lower damage levels, ‘MD’ and ‘LD’ occurring at comparatively moderate blast conditions, have not shown to be significantly dependant on column orientation. These lower damage levels are not noticeably influenced due to overall column stiffness; instead, they tend to be dependent on material fracture and localised fragmentation characteristics of high-rate loading conditions such as blast.

**Figure11:** Column residual axial capacity versus column orientation: vented blast condition

**Figure12:** Column residual axial capacity versus column orientation: contained blast condition

The assessment charts shown in Figures 13 and 14 demonstrate the effect of column clear height on their vulnerability to vented and contained internal blast conditions respectively. Increasing the clear height resulted in an increase in the column vulnerability to damage classes ‘*SSD\**’ and ‘*SSD*’; due to increased slenderness and reduced overall lateral stiffness of the column. This behaviour is in contrast to the influence of column clear height on the lower damage classes (*MD*

and *LD*). In this case, increasing the clear height only marginally influenced the threshold lines of ‘*MD*’ and ‘*LD*’ damage levels.

**Figure13:** Column residual axial capacity versus column height: vented blast condition

**Figure14:** Column residual axial capacity versus column height: contained blast condition

Overall, the assessment technique discussed in this paper can be used to promptly obtain the extent of column damage and consequential residual axial capacity level due to a range of internal blast conditions. It is believed that these outputs will be of significant relevance to protective design of RC columns subjected to complex loading conditions due to internal building detonations.

1. **Conclusions**

This paper detailed the development of a damage assessment protocol for RC columns subject to time-variant coupled uplift and lateral blast pressures induced due to internal building detonation scenarios. This was based on a comprehensive parametric study conducted using an advanced uncoupled numerical modelling technique comprising high-resolution CFD simulations and Applied Element numerical modelling of column response. The developed assessment charts quantify the extent of internal-blast-induced damage in RC columns in terms of residual axial capacity and overall failure mechanism. This paper also discussed the influence of design compressive strength of concrete, column orientation and slenderness on the damage behaviour and residual axial capacity of RC columns due to different internal blast conditions. The extent of overall damage in columns decreased with increasing compressive strength of concrete. Importantly, both column orientation and slenderness noticeably influenced the vulnerability of columns to higher damage classes (severe structural failure and imminent collapse) that are primarily governed by overall column stiffness and strength. In contrast to this, lower damage classes (concrete fracture and minor localised spallation) were not noticeably dependant on column orientation and slenderness.

Overall, the assessment protocol presented in this paper can be used to conservatively assess the vulnerability of RC columns subjected to internal blast actions. From this perspective, it is expected that the content of this paper will contribute towards the protection of civilian infrastructure against future threats including both explosive attacks and accidental explosions. Importantly, this research area is extensive and requires further comprehensive investigations to address a wide spectrum of engineering challenges. In this respect, it is also expected that this paper will contribute towards attracting a public debate and promoting further research on this topic.

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