Probabilistic Blast Assessment for Reinforced Concrete Bridge Columns

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Abstract– Transportation systems are integral to a community's growth and development. Reducing vulnerability and creating a resilience transportation system has becoming a prevalent trend in developed countries such the United States and Canada. Egypt has been no outlier to this approach. A beaming spotlight has been put on columns especially, columns which are often considered as bridge primary component with high hazard exposure (i.e. impact and blast). Current codes of practice are mainly based on a deterministic design basis threat, this type of design only analyzes based on the given parameters and incorporates little insight to uncertainties. Numerous researchers have studied the impact of far and near field testing on reinforced concrete columns while others have created and verified computer-based models to simulate the real-life experiments. However, the specific investigation of the influence of blast wavefront uncertainty on the performance of reinforced concrete bridge column under blast loading is extremely limited. As such, the presented study focusses on investigating the probabilistic performance of columns subjected to blast loading. This objective is accomplished initially by creating an OpenSees Model that successfully simulates an ordinary bridge column experiencing a blast load created from a terrorist attack scenario. Furthermore, an iterative probabilistic framework was implemented to facilitate a Monte-Carlo simulation for the considered column. Finally, the results were presented as fragility curves that is considered the base of blast risk assessment for reinforced concrete bridges.

I. INTRODUCTION

The study of blast and its devastating effects on structures has become an increasingly critical aspect in our modern design. The soaring increase in the number of localized hazard events has influenced designers to pivot philosophies from Pareto Efficient, which is notorious for its highly optimized efficiency and minimal cost (UNISDR 2012), to a resilient based system, who on the other hand has a keen focus on the systems functionality, robustness, and post hazard recovery time (Linkov et al. 2014). Statistical data gathered since 2001, shows that the recorded number of bombings and explosions world-wide displays an increasing trend with a distressing peak occurring in 2007, approximately 1805 blast related incidents occurred (START 2016). With regards to the locations of these terrorist attacks, the United Nations Office for Disaster Risk Reduction (UNISDR 2012) claims that half of the world's population and wealth and assets is clustered in urban centers around the world, these centers are notoriously the main target of terrorist attacks.

Even though bridges are perceived as a central element among the many infrastructures present in these urban centers, it is also unfortunately the most vulnerable (Merschman et al. 2020). Fundamentally, bridge columns are considered one of the main sources of bridge vulnerability (Goodnight et al. 2016). The vulnerability of bridge columns is a direct consequence of the continuous exposure of such element. Bridge columns are constantly being prone to multiple hazards, hence indirectly resulting in the high occurrence of hazards near bridges (Bruneau et al. 2017), not as different components that can be protected (for example: foundations, bearings). This encompasses not only man-made hazards either accidental or intentional (i.e. terrorist attacks) but also natural hazards (such as: earthquakes, tsunamis, etc.). More often, bridge columns are left on islands between highway lanes with inconsiderable amount of protection which magnifies its vulnerability. As such, numerous researches have addressed the vulnerability of bridge columns from the multi-hazard attribute (Bruneau et al. 2017). However, most of these published studies focusses on the structural performance of columns under different hazards either experimentally or numerically without addressing the impact such column vulnerability on the bridge probabilistic performance.

As such, the presented study focusses on investigating the probabilistic performance of columns subjected to blast loading which is considered as a black swan event (i.e. low probability, high consequence event) (Salem et al. 2018). The presented work firstly focusses on developing a simple model for concrete columns subjected to blast load (low computational effort) which is later validated against already published data base. Secondly, the developed model will be integrated in a Monte Carlo simulation analysis to account for different blast wave parameters uncertainty, namely reflected peak pressure (P_r) and specific impulse (I_s). The Monte Carlo simulation will later facilitate the development of fragility curves which can facilitate risk-assessment. This paper aims to address the new paradigm of probabilistic assessment rather than the currently used deterministic approach (ASCE 2011; CSA 2012) (Salem et al. 2017).

II. LITERATURE REVIEW

Blast wave properties:

A. Positive wave

Blast wave is defined as a rapid rise and decay from the Ambient Atmospheric Pressure (often assumed to be one bar) due to chemical reaction of the explosive materials. The maximum pressure rise is defined as Positive Peak pressure (P_r). The time it takes for the explosive device initial shockwave to reach the structure is known as the Arrival Time (t_a). The positive phase pressure is usually described using the Friedlander's equation as shown in Eq. (1).

$$P(t) = P_o + P_r\left(1 - \frac{t}{t_{pos}}\right) e^{-b\left(\frac{t}{t_{pos}}\right)} \quad (1)$$

Where t_{pos} is Positive phase duration and **b** is Wave Decay parameters.

On the other side, impulse of the incident pressure is a measure of energy generated with an explosive device when detonated. Similar to pressure, impulse measurements consist of both positive and negative readings (Goel, 2020). The Impulse created from a blast wave is calculated using the Friedlander's curve, it is the denoted as the area under the blast pressure profile as shown in Eq. (2).

$$I_s = \int_{t_a}^{t_a+t_o} (P(t)).dt = P_{max} t_0 \left(\frac{e^{-b}+b-1}{b^2}\right) \quad (2)$$

Where, I_s is the Specific Impulse, *b* is Wave Decay Parameters. In the case of this research, the impulse was simplified to idealized triangular load which has been proven as a reasonable assumption for the blast wave (Salem et al. 2021). The used I_s equation is elaborated in Eq. (3).

$$t_d = \frac{2I_s}{P_r} \quad (3)$$

B. *Negative wave:*

Negative wave pressure is directly proportional to the angle of incidence and is represented on the Friedlander curve as the region were the curve dips below the ambient pressure. Many researchers and designers overlook the effects of the negative pressure phase on the structure. However, it was concluded that the negative wave pressure does damage for flexible non-structural components such as doors, windows etc. (Goel, 2020). As such, the influence of the blast negative phase has been neglected in the presented work.

Blast wave uncertainty

The deterministic approach used by the North American blast standards (ASCE 2011; CSA 2012) is typically conducted using given design parameters. However, numerous researches have been focusing on the assessment of different uncertainty sources associated with blast risk. For instance, (Stewart 2010) established a framework that probabilistically assessed various method for blast risk mitigation and then proceeded to quantify risk in terms of casualties per building. The scope of this framework was contained the two main sources of uncertainty,

1. Epistemic uncertainty, it encompasses both Loading and Model uncertainty.
2. Aleatory uncertainty, this mainly accounts for inherent variability.

Amongst the proposed frameworks, (Campidelli et al. 2015) particularly assessed the uncertainty in the blast wavefront parameters predictions. More specifically, the *Pr* and Is were fitted to a gamma and normal distributions with a mean of 0.99 and 1.01 and a c.o.v. of 0.18 and 0.19 respectively. These uncertainty parameters were integrated with the numerical model demonstrated below to address the epistemic uncertainties and to develop the fragility curves (i.e. aleatory uncertainty). The developed fragility curves were derived based on the performance limits recommended by the ASCE (2011), which are categorized into 3 groups: light, moderate, and severe. These damage states (DS) are associated with the support rotation not greater than 2.3, 4.6 and 8.5 degrees, respectively.

III. MODEL DESCRIPTION

OpenSees Model

The foundation of this research is an OpenSees model. The parameters used to describe and define the blast load are the P_r and the arrival time of the wave (t_d), which subsequently accounts for the I_s. The inputs for the OpenSees Model are primarily Mass, Geometric dimensions of the column (length, width, and height), number of steel reinforcement in the section, material properties for both concrete and steel (concrete compressive strength, steel yielding strength and modulus of elasticities) and the load (this encompasses both axial and blast loads).

Iterative framework

The analysis method in this research paper is accomplished with two programs, OpenSees and MATLAB. Open System for Earthquake Engineering Simulation or simply OpenSees is an open-source program is used to build finite element applications for simulating the dynamic response of structural, specifically Earthquake analysis. Salem at al. (2021) proposed a similar modelling technique to assess the uncertainty of blast wavefronts on reinforced concrete block masonry shear walls. As for blast modeling, Dynamic Increase Factor (*DIF*) is considered an important parameter that should be included in the model. Unfortunately, OpenSees is heavily restraint in that regard. As such, a MATLAB iterative model that incorporated the initial OpenSees model, its outputs, with DIFs equations for all the material properties affected by the blast loading.

To initiate the framework, the initial DIFs assumption for the considered materials 1, this current value for the DIF is then multiplied with the concrete compressive strength, steel yielding strength and modulus of concrete elasticity, however this assumption will only be the case in the first iteration. Once these values are computed, the subsequent task is dynamic analysis.

As previously described in the section above, OpenSees is utilized to completed it. The value of hinge moment experienced in the first iteration is then compared to the M_y, which was calculated from the Fiber Analysis, which may result into:

1. $M > M_y$, in this case the initial assumption of the DIFs of the concrete compressive strength, steel yielding strength and modulus of concrete elasticity were incorrect and thus must be evaluated using the equations as described in the Euro Code.

2. $M < M_{y}$, in this case since the yielding was not reached. As a result, the time required by the rotational spring to reach yielding capacity (h_y) is equal to zero, which means that the hinge is not yielded yet, and the column stays in the elastic stage. Consequently, all DIFs are automatically valued as 1. Salem at al. 2021, includes further details about the used model.

The aforementioned framework is summarized in Fig. (1).

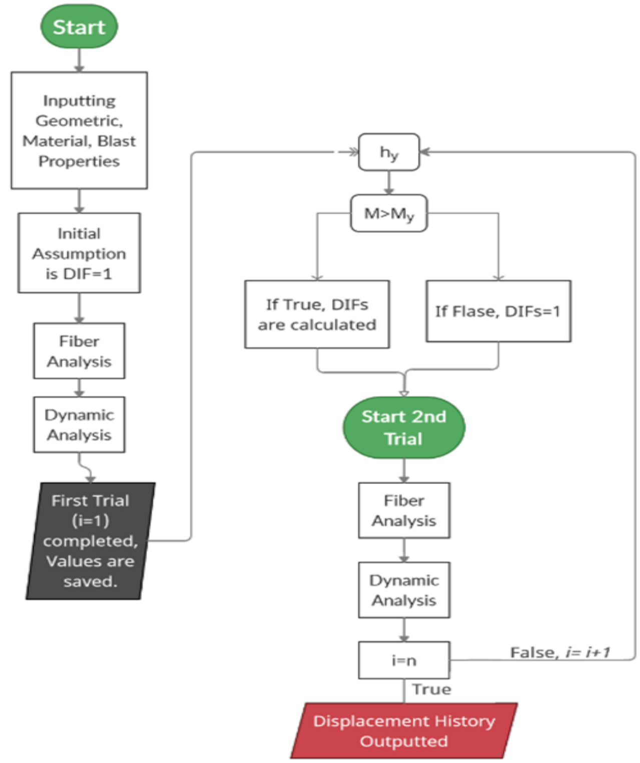

Fig. 1. Probabilistic blast analysis iterative framework

IV. VALIDATION PROCESS

The first trial carried out by the iterative framework is entirely for validation purposes, the data used for validation was attained from a numerical parametric investigation (that was also validated experimentally) conducted by Astarlioglu et al. (2013). Five columns were selected for validated the current model. The boundary conditions of the validating columns were classified as fixed-fixed. All the columns were designed to resist mainly gravity loads and would be a part of a system such as a Moment Resisting Frame that would globally resist lateral loads. All the selected columns were designed with various reinforcement ratio and in accordance with the ACI Code of Practice (ACI committee 318 2014). The columns were with a square cross section of 406mm length (as shown in Fig. 2) and 3600mm height. Whereas the concrete density was assumed be 2,400 kilograms per cubic meter. All the columns had eight vertical rebars with diameters sizes: 22.225, 28.65, and 35.81 mm. The traversal steel reinforcement was US No. 4 with a diameter of 12.7mm and cross-sectional area of 129 mm^2, the spacing between stirrups were 304 mm. The concrete compressive strength (f_c) and reinforcement yielding strength (f_y) were 27.6 MPa and 413.7 MPa, respectively. Table 1 summarizes the validation database including the reference mid-height deformation as well as its corresponding result obtained from the developed model. The developed model showed an average deviation of 5.7% which is considered an acceptable error due to the aforementioned model simplifications.

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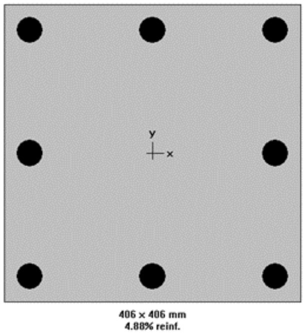

Fig. 2. Cross-section of the column used for validation

Table 1. Validation database

No.	**Peak Pressure (kPa)**	**Rft Bar No.**	**Rft. Diameter (mm)**	**Mid-Span Displacement (mm)**	**Model results (mm)**	**Percentage of Error (%)**
1	5100	No. 9	28.65	11	11.78	6.65
2	5100	No. 11	35.81	10	11.45	12.66
3	5100	No. 11	35.81	10	10.82	7.54
4	5100	No. 11	35.81	14	12.58	-11.25
5	8200	No. 9	28.65	22	25.56	13.94

V. DEVELOPMENT OF COLUMN BLAST FRAGILITY CURVES

The investigation carried out in this section specifically addresses the uncertainty linked with I_s and P_r on the blast performance of reinforced concrete columns. The same validation column was used in this investigation to insure a good confidence for the expected recommendations. The used column can be a part 4 column pier connected to a pile cap and a rigid hammer head.

By combining pseudo-random sampling from a Monte-Carlo simulation and the previously stated iterative framework, the influence on I_s on the bridge column is mapped in the form of fragility curves. It worth noting to mention that the present investigation assumed a constant average P_r, (10200 kPa) while maintaining its c.o.v. (Campidelli et al. 2015). Fig. 3 depicts the fragility curve for the considered column showing the probability of reaching each damage state with respect to $I_{s.}$ The considered damage state resulted into a mid-span deflection of 73.5, 147.24, and 273.5 mm for the three ASCE damage states. This figure demonstrates the fragilities at different damage states, namely, light, moderate, and severe. Overall, the three curves show a similar trend, it requires a bigger blast (i.e. impulse) to surpass each subsequent damage state. For example, the column showed 50% probability of reaching the light, moderate, and severe damage states at I_r of 6750, 11500, 18000 kPa.ms respectively. These finds were similar to my expectations and coincides with that of previous literature which echo these similar findings. The generated fragility curves are considered the first step toward comprehensive blast risk assessment.

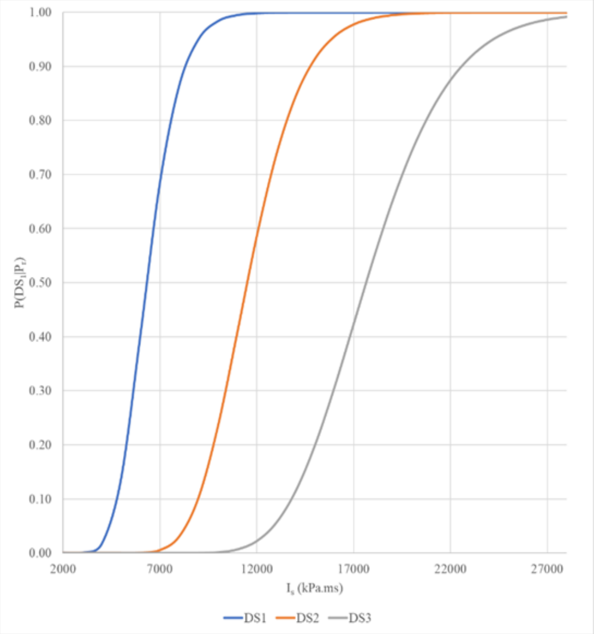

Figure 3. Typical blast fragility curves for the considered RC columns

VIII. CONCLUSION

This paper targets challenging the currently dominate deterministic philosophy for blast assessment by proposing a probabilistic framework that takes in consideration different blast wave parameters uncertainties. The investigation undergone in this paper evaluates the blast performance of reinforced concrete bridge columns under the effects of wavefront parameters uncertainty, specifically reflected peak pressure (P_r) and specific impulse (I_s). Objectively this was achieved by using a finite element analysis program (OpenSees) coupled with an iterative framework whose role was to facilitate the iterative calculation of DIFs. The proposed framework was initial inspirated by previously developed model, however some modifications were required to apply it on columns. Ultimately, it was able to simulate the mid-span deflection of the bridge column with a mean deviation of 10.41%.

Although this paper addressed a fixed-fixed column, however, in real life different support configurations can be done. Moreover, for future studies, it would be recommended to conduct different parametric investigation including the geometry and material, which may affect the concluded results greatly.

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