Structural Reliability Analysis of SFRP-Reinforced Bridge Columns Exposed to Blast Load

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ABSTRACT

The vast majority of bridge structures in North America are designed without consideration of blast load. In recent years, however, recognition of this type of threat has become more pronounced. For existing structures deemed to need blast protection, a potentially effective and cost-effective option is external wrapping with steel fiber reinforced polymer (SFRP), a material that is less expensive than carbon fiber fabric as well as ductile. Although research has demonstrated that SFRP wrapping increases blast resistance, whether such protected columns can meet the target reliability level expected by current bridge design standards is unknown. This issue is addressed in this study, where the reliability of typical reinforced concrete bridge columns strengthened with externally bonded SFRP fabric subjected to blast loads was investigated. Columns were modeled with a nonlinear finite element approach, validated to experimental data, that considers material damage, fracture, and separation. Different concrete strengths, longitudinal reinforcement ratios, and gravity and blast load levels were considered, while uncertainties in concrete, steel, and SFRP material strength and stiffness parameters, as well as blast, dead load, and vehicular traffic loads, were incorporated in the probabilistic analysis. These uncertainties were represented with 79 resistance and 6 load random variables, with statistical parameters taken from the available literature. The Failure Sampling approach was used to assess column failure probability across a wide range of blast loads, where results are reported in terms of generalized reliability index. Depending on column characteristics and applied loads, it was found that the use of SFRP can allow exposure to significant increases in explosive charge weight without loss of column reliability level.

1. INTRODUCTION

Nearly all highway bridges in the United States are designed according to the American Association of State Highway and Transportation Officials LRFD Bridge Design

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Specifications (AASHTO LRFD 2020). Although AASHTO specifies a limit state combination with blast load, no blast-related design provisions are given, nor are criteria for determining the necessity of designing a structure for blast. Although blast load may affect any part of the structure, of particular concern are the central piers (columns) common to multi-span structures that bridge divided highways. These columns are readily accessible, and if damaged severely, may cause the ends of both spans to collapse.

Rather than the design of new columns, which has been addressed elsewhere (Winget et al. 2005; Williamson et al. 2011; Yi et al. 2014) this study is concerned with the large inventory of existing bridge columns that were not designed for blast mitigation. A cost-effective and minimally disruptive approach to enhance the blast resistance of the structure may be to strengthen rather than replace the existing columns. This possibility was investigated by several researchers, including Malvar et al. (2007), Fujikura and Bruneau (2011), and Heffernan et al. (2011), with external wrapping or jacketing. Recognizing that significant uncertainties exist in load and resistance parameters, several studies examined reinforced concrete column reliability under various blast load scenarios (Hao et al. 2016; Shi and Stewart 2015; Thomas and Sorensen 2018).

Of the various strengthening options available, the focus of this study is the use of column wrapping with steel fiber reinforced polymer (SFRP) fabric, which is significantly less expensive than CFRP as well as ductile. Only a few studies have considered the effect of SFRP on column blast resistance, and the reliability of such strengthened columns remains unquantified. Given that the AASHTO LRFD Specifications were probabilistically calibrated to a minimum reliability level, a reliability-based approach for the evaluation of safety level is appropriate. Therefore, the objective of this study is to estimate the reliability of a typical RC bridge column retrofitted with externally-bonded SFRP when subjected to blast load.

2. COLUMN CHARACTERISTICS

Characteristics of the considered column are based on typical designs used by many Departments of Transportation (Eamon et al. 2018). In this study, the upper range of column size, 914 mm square and 5 m unsupported length, was considered for analysis, to represent the larger range of common bridge designs which are perhaps more prone to blast attack. Concrete compressive strengths (f'_c) from 28-55 MPa were considered, as were longitudinal reinforcement ratios (ρ) from 0.015-0.042. Longitudinal reinforcement consists of 7 bars per face, where bar area was varied to produce the reinforcement ratios given above. Typical 13 mm stirrup ties were spaced at 300 mm, a spacing commonly used in the design of bridge pier columns. Reinforcing bars are taken to have yield stress of 414 MPa, with concrete cover of 50 mm. Note that construction and maintenance concerns tend to govern these column designs rather than gravity loads, typically resulting in columns with axial load capacities greatly exceeding the minimum required.

The properties for SFRP wrap are taken from commercially available products (Hardwire 2014), where the considered fabric is composed of a 1.2 mm thick polymer sheet which contains unidirectional, high-strength steel strands with yield strength of 985 MPa and an effective elastic modulus of 66.1 GPa in its strong direction. The SFRP sheets are adhered to the column with epoxy resin after appropriate preparation of the concrete surface, with the strong direction oriented horizontally.

3. LOAD MODELS

Nominal dead loads on the column were determined assuming that the central pier supports the ends of two bridge spans, where each span is 18.3 m long and 13 m wide, representing a typical two-lane bridge deck. The reinforced concrete deck is taken to be 228 mm thick and is supported by seven steel girders spaced at 1.9 m. The central pier is composed of four columns that support a pier cap on which the girder bearings rest, a bridge configuration typical of structures built by various state DOTs (Eamon et al. 2018).

Dead load random variable statistical parameters are based on those used in the AASHTO LRFD calibration (Nowak 1999), and include those from prefabricated (D_p) and site-cast components (D_s), as well as from the deck wearing surface (D_w). All dead load random variables are taken a normally distributed.

Because axial load on the column was found to affect reliability when exposed to blast, different axial load levels were considered for comparison, including dead load alone as well in conjunction with vehicular live load. For the latter case, vehicular live load statistics are also taken from those developed for the AASHTO LRFD calibration, where a range of statistical parameters were considered that represent maximum traffic loads corresponding to daily maximums to maximums expected throughout the 75 year bridge design lifetime.

Blast pressure is represented with the CONWEP model (Hyde 1988), which is based on a modified form of the Friedlander Equation fit to experimental data of various blast pressures found from a variety of charge weights and standoff distances. The resulting blast pressure at a particular point away from the source is represented with the scaled distance parameter Z, which is a function of the explosive weight and distance: $Z = R / W^{1/3}$, where R is the distance from the blast initiation point to the column face (m), and W is the explosive weight, in terms of equivalent mass of TNT (kg). Based on an inspection of blast-damaged bridges in Iraq, the mean charge placement is taken as 1 m away from the column, with a 50 mm height above the ground surface. Two random variables are used to describe the uncertainty in scaled distance: the effective charge weight (Q_w) and the resulting blast pressure equivalency (Q_e), where Q_w has a Gaussian distribution and Q_e a triangular distribution. Statistics for these parameters are taken from Shi and Stewart (2015).

4. RESISTANCE MODEL

The FEA approach used to evaluate column capacity is taken from Alsendi and Eamon (2020), which was reported to well-match experimental data. In this approach, concrete is modeled with the Johnson-Holmquist-Cook approach (Holmquist et al. 1993), which was specifically formulated for the large strains, high strain rates, and high pressures associated with blast loads. The constitutive relationship of reinforcing steel is represented by a kinematic, elastic-plastic model, where nominal yield stress is taken as 414 MPa, Young’s modulus 200 GPa, and post-yield modulus 20 GPa. The Copwer and Symonds approach (Livermore Software Technology Corporation 2018) is used for strain-rate strengthening, where specific material parameters are taken from Bai and Jin (2016). An anisotropic model is used to characterize the SFRP sheet, with Young's modulus and yield stress nominally taken as 66.1 GPa and 985 MPa in the strong direction, with a Poisson ratio of 0.30. Based on typical resin properties, the SFRP bond is modeled with a shear strength of 32 MPa and a normal (tensile) strength of 29.4 MPa. Hexahedral elements were used to model the column concrete, reinforcing bars were modeled with beam elements, and the SFRP was modeled with shell elements. SFRP elements are linked to the column with a contact surface, with attachment strength representing the resin bond strength between the concrete and composite wrapping. These models were explicitly solved with a large strain, large displacement Lagrangian FEA approach that allows element disintegration, separation, and contact, as implemented in LS-DYNA (Livermore Software Technology Corporation 2018).

Resistance random variables are taken as material strength and stiffness parameters, and include concrete compressive strength (f'_c); yield stress of the longitudinal bars (F_{yl}), stirrup ties (F_{yt}), and SFRP (F_{yS}); Young's modulus of the longitudinal bars (E_l), stirrup ties (E_t), and SFRP (E_S); and tangent modulus of the longitudinal bars (E_{Tl}), stirrup ties (E_{Tt}), and SFRP (E_{Ts}). As it was found that the level of correlation between stirrup tie properties did not significantly influence results, corresponding properties between stirrup ties were thus taken as fully correlated to simplify the reliability model. This resulted in 24 random variables each for yield stress, elastic modulus, and tangent modulus to describe uncertainties in the 24 longitudinal bars, and one random variable for each of these three parameters to describe all stirrup ties, and two random variables to describe the SFRP fabric. Statistical parameters are taken from Nowak and Szerszen (2003), Eamon and Nowak (2005), Wisniewski et al. (2012), and Val and Chernin (2009). All are reported as normally distributed.

5. RELIABILITY ANALYSIS

The limit state function is written in terms of the axial load capacity of the column, where failure is defined as the event where the column can no longer support the axial load imposed and begins to collapse, while subjected to the blast load described above. Using the FEA model above to evaluate column resistance and responds to blast, failure probability was computed with the Failure Sampling method (Eamon et al. 2020), an approach specifically developed for efficient evaluation of complex, moderate to high reliability problems.

To assess column reliability across a variety of small to moderate blast threats, the analysis was conducted for a range of scaled distances from approximately 0.1 to 0.3 m/kg$^{1/3}$. As the axial load on the column was found to affect reliability under blast, two axial load cases were considered: dead load (DL) and nominal load (NL). The DL case includes only the self-weight of the structure and represents the most likely scenario when the column is subjected to blast load. As axial forces caused by typical traffic loads were found to have little influence on reliability under blast load, the theoretically higher NL level of load was considered, which represents the maximum unfactored load that the column can support, per AASHTO LRFD design criteria. Failure probability (p_f) results were converted to generalized reliability index β (i.e. $\beta = -\Phi^{-1}(p_f)$) for ease of comparison to established levels of code reliability.

6. RESULTS

Results are shown in Figures 1 and 2 for columns without (solid line) and with (dotted line) SFRP strengthening, for longitudinal steel reinforcement ratios of 0.015 and 0.042, respectively. As expected, reliability index increases as scaled distance increases (and thus as effective blast load decreases), and the reliability index of the bare columns and those wrapped with SFRP tends to converge as blast load is increased. This occurs because as blast load increases, reliability becomes more dominated by load effect rather than SFRP resistance characteristics. Also as expected, increasing concrete strength significantly increases reliability for low to moderate blast loads. For columns with higher reinforcement ratios similar trends are shown, but column reliabilities are generally higher, as expected. As compared to increasing concrete strength or internal reinforcement, the benefit of SFRP is measurable but less significant. Similar to changes in concrete strength, the largest benefits from SFRP occur at low and moderate blast loads. Interestingly, a significant benefit in blast reliability is realized by increasing the mean axial load on the short columns considered (buckling is not a concern), from the DL to NL load level, where enhancements in reliability due to increases in concrete strength or the use of SFRP become more pronounced. The increased axial load practically serves as prestressing, lowering tensile stresses and inhibiting the crack development and growth that ultimately causes base failure. For comparison to current standards, note that that minimum acceptable reliability index for bridge members according to the AASHTO LRFD Specifications is 3.5 (Nowak 1999).

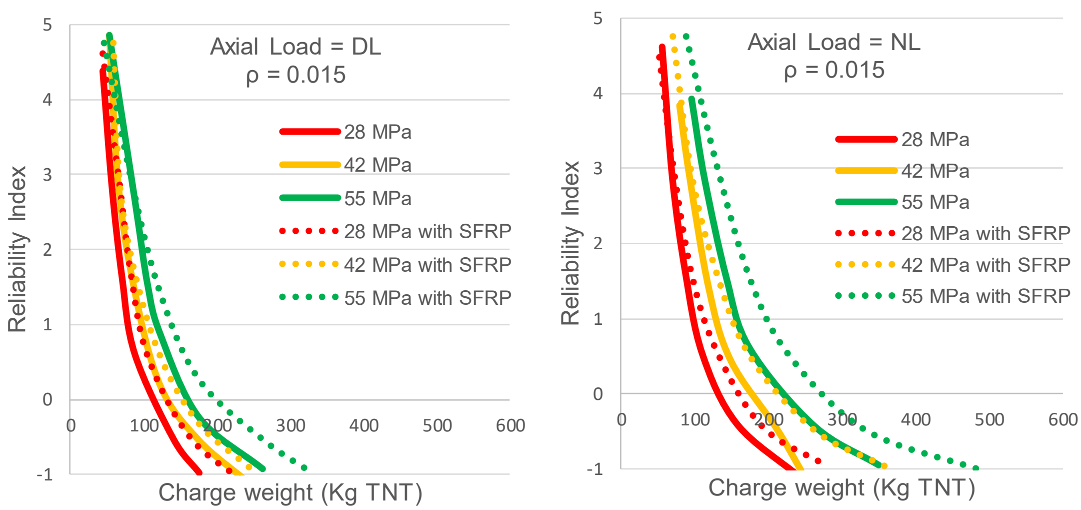

Fig. 1 Reliability results, 0.015 reinforcement ratio

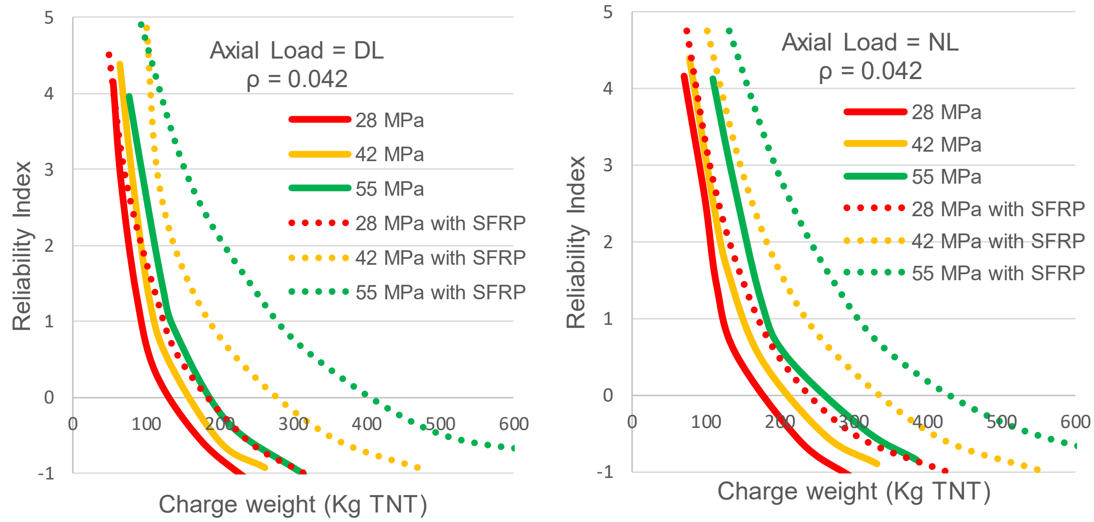

Fig. 2 Reliability Results, 0.042 reinforcement ratio

For the columns and blast scenarios studied, consider those subjected to the most likely (and conservative) DL axial load condition. To meet the minimum reliability target of 3.5, columns with no SFRP applied can be subjected to Z values from 0.23-0.28 m/kg$^{1/3}$, depending on concrete strength and reinforcing ratio. With SFRP, the scaled distance can be decreased to 0.19-0.26 m/kg$^{1/3}$ while meeting the same level of reliability. Although these differences appear small, they represent substantial changes in charge weight for a given distance. For example, considering a closely placed charge at 1 m from the column face, the equivalent change in weight varies by a factor of 1.2-1.75, where larger increases in charge weight occur for columns with higher concrete strengths and reinforcing ratios.

7. CONCLUSIONS

It was found that for the columns and blast scenario considered, reliability under blast is most significantly increased by raising concrete strength, followed by SFRP wrapping, then by increasing steel reinforcing ratio. It was further found that the degree to which SFRP wrapping benefits column reliability varies with blast level and column characteristics, where greater enhancements generally occur for lower blast loads and higher strength columns. For the cases considered, strengthening columns with SFRP enables maintaining a reference reliability index of 3.5 while subjected to decreases in scaled distance from approximately 5-20%, differences that represent substantial increases in allowed charge weight at close distance. Because SFRP wrapping is a relatively inexpensive retrofit option, results of this study suggest that it may be viable for blast protection of existing bridge columns, when maintaining a given level of reliability is of concern.

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