ABSTRACT

The wrapping of columns with Fiber Reinforced Polymer (FRP) sheets has become a common technique for the protective hardening of reinforced concrete columns against blast pressure effects. FRP wrap provides added strength and ductility, resulting in an economical solution to harden existing columns subject to blast threats. This paper investigates the effectiveness of FRP wrapping on typical reinforced concrete columns subject to various blast pressures and with different wrapping configuration. Single-degree-of-freedom (SDOF) analyses of the unwrapped and wrapped columns are carried out with FWrapSDOF, a proprietary SDOF analysis code for simulating the response of FRP wrapped columns to blast loading. The SDOF results are compared with the actual test results of unwrapped and wrapped columns subject to various blast pressures and with different wrapping configuration. This is to evaluate the fidelity of SDOF analyses for FRP wrapped reinforced concrete columns.

KEYWORDS

FRP, SDOF, columns, blast, protection.

INTRODUCTION

The aim of this paper is to describe a retrofit design procedure that incorporates documented enhancement effects, from an FRP retrofit, into well-established software, which is based on the SDOF methodology. This design procedure is to aid in the retrofitting of existing RC columns, where improvement to its lateral resistance is required.

The retrofit design procedure and comparisons described herein is qualitative in nature. Quantitative measurements and comparisons, for the evaluation of the accuracy and effectiveness of the design procedure, are to be further assessed and verified with additional testing in the future.

BASIS OF FWrapSDOF SOFTWARE

Single-Degree-Of-Freedom (SDOF) Analysis

Several different dynamic analysis methods are available for blast resistant design. These approaches can range from simple hand calculations and graphical solutions, to more complex computer based applications. The decision on which approach to adopt is usually based on the consideration between obtaining results of sufficient accuracy and the complexity of the calculations involved.

The basic analytical model used in most blast design applications is the SDOF analysis approach. Although all structures possess more than one degree of freedom, many structures can be adequately represented as a series of SDOF systems for analytical purposes. Furthermore, sufficiently accurate results can be obtained for primary load carrying components such as columns.

Various publications prescribe well-documented methods to compute the equivalent SDOF system properties for various types of structural components.
**SDOF Blast Effects Design Spreadsheets (SBEDS)**

*Background*

The SDOF Blast Effects Design Spreadsheets (SBEDS) is a product of the U.S. Army Corps of Engineers Protective Design Center and was developed by Baker Engineering and Risk Consultants, Inc. (BakerRisk). It is an Excel® based tool for the design of structural components subjected to dynamic loads, such as an airblast, using the SDOF methodology.

Contained within SBEDS are worksheets, for common structural components, which allow a user to input available parameters, related to material properties and structural geometries, in order to calculate the SDOF properties.

The foundation of SBEDS is an SDOF numerical integration scheme capable of analysing a resistance function with multi-linear segments for initial response, as well as for rebound (Figure 1). The calculations are performed using a constant velocity numerical integration scheme, as generally recommended, to solve the SDOF equations at each time step.

*Reinforced concrete beam-columns with combined compression and lateral load*

For an SDOF analysis of a reinforced concrete column that is required to carry vertical loads, in combination to being subjected to lateral blast loads, the ultimate flexural resistance of the column can be calculated based on the interaction diagram (Figure 2) between axial load and moment capacity in a short column, which is very similar to the interaction diagram used for static design.

In SBEDS, the ultimate moment capacity of a reinforced concrete beam-column is calculated by developing the interaction diagram (Figure 2) based on equations defined in Chapter 10 of UFC 3-340-01, except that a straight line is conservatively assumed between Mo, the dynamic moment capacity without axial load, and the balanced condition (Pb,Mb).

**FWrapSDOF**

*Retrofit design procedure*

Using the SBEDS and its methodology as the cornerstone, the FWrapSDOF was developed to retain the user-friendliness of the beam-column spreadsheet in SBEDS, and at the same time incorporate the retrofit design procedure. The modifications made were heavily influenced by ACI 440.2R-08, while other FRP guides were referenced for consistency.

The modifications incorporated can be grouped into three main areas of interest: concrete confinement due to FRP hoop wraps, flexural enhancement due to FRP flexural wrap and shear contribution from steel links as well as FRP hoop wraps. Effects associated with FRP bonding to concrete, aging or degradation, which reduces the strength of the FRP contributing to the ultimate capacities of the column, are addressed by the factors recommended in ACI 440.2R-08 (Figure 3 and 4).
With the modifications made to these three areas, the resistance-deflection curve, which originally only plotted the flexural response of the column, has been modified to reflect the column shear capacities, as well as the expected deflection from the lateral loads (Figure 5).

**Confined concrete model**

The confinement of reinforced concrete columns, by means of FRP jackets, can be used to enhance their strength and ductility. For the development of the FWRapSDOF for column retrofit, the stress-strain model developed by Lam and Teng (2003a,b) has been adopted (Figure 6). This model characterises the main aspects of the behaviour of FRP-confined concrete in a simple form and its usefulness and accuracy can be seen from its adoption by the Technical Report No. 55, ACI 440.2R-08 and ICC AC125 documents.
The equations for the FRP-confined concrete model are extracted from ACI 440.2R-08 and computation of the various components is as illustrated in Figure 7. As these equations are computed based on concrete cylinder strength, an option was built into the program to consider input based on concrete cube strength. An additional option provided allows the user to decide whether to consider confined concrete enhancement or not (Figure 8).

![Confined Concrete Model](image)

**Figure 7: Computations for FRP-confined concrete model**

**Flexural capacity**

For the consideration of flexural enhancement with FRP layers, the user is required to select the FRP System and provide the number of layers to apply (Figure 8). Indication of the exposure condition is for the consideration of the environmental reduction factor (Figure 3 and 4).

For simplification of the design, the FRP for flexural wrap is considered to strengthen the positive moment region only. Enhancement to negative moment region is assumed to be physically impractical.

FRP on compression face is conservatively taken to not increase moment capacity, moment of inertia or axial load capacity. The fibre on faces adjacent to the tension face, which may partially experience tension, is also not taken into consideration. The average sectional stiffness for the reinforced concrete column is taken as the average of the cracked and gross sections, as proposed by TM5-1300.

![User-input options for retrofit using TYFO® Fibrwrap® Systems](image)

**Figure 8: User-input options for retrofit using TYFO® Fibrwrap® Systems**

**Diagonal shear capacity**
In FWrapSDOF, the user is able to consider the existing steel shear links (Figure 9) in the design. The inputs will go towards the computation of the shear capacity provided by the steel shear links and is computed based on ACI 318-05 (Figure 10). For the shear strength reduction factor, \( \phi \), it is provided as an option for the user to decide (Figure 8).

For the FRP’s contribution to shear strength, all computations are based on the assumption that the columns are wrapped completely. When hoop wraps are considered, the concrete shear capacity is based on the full thickness of the cross section, implying that the distance “d” is based on the fibre reinforcement at the column face rather than at conventional reinforcing steel with a cover depth.

**Live Test**

A retrofit using TYFO® SCH-41-2X carbon horizontal wraps was designed, applied, and validated with a blast load in a full-scale field test (Figure 11). The objective of the test was to explore the effectiveness of the FRP system in protecting the columns against close-in threats. This test has demonstrated that retrofitting RC columns with the TYFO® Fibrwrap® Systems is an efficient means to ensure the survivability of columns subjected to close-in blast loads.

When the same test parameters were applied into FWrapSDOF, the results were in consistent agreement that with the provision of the carbon hoop wraps, the columns are sufficiently protected against potential diagonal shear failure.
CONCLUSIONS

The design methodology adopted for the modification of an existing design program was described. The modification applied is for the consideration of retrofitting existing RC columns with composite wrap to improve their resistance to blast loads.

Both the flexural and diagonal shear capacities of conventional reinforced concrete columns can be upgraded to prevent excessive lateral deflections and shear failure. A qualitative comparison, between observations made in a live test with the runs made on the modified program, shows congruence.

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