HBRC Journal (2015) xxx, xxx–xxx

Housing and Building National Research Center

HBRC Journal

http://ees.elsevier.com/hbrcj

Three-dimensional nonlinear finite element analysis of concrete deep beam reinforced with GFRP bars

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Received 20 June 2014; revised 2 November 2014; accepted 19 February 2015

KEYWORDS

Deep beam;
GFRP bars;
Finite element;
ABAQUS

Abstract The efficient use of FRP reinforcement in deep members has been hindered due to a lack of knowledge on the behavior of such members. Till now, most of researches have mainly focused on the flexural or shear behavior of shallow members longitudinally reinforced with FRP and most of them used testing at small scales. This paper presents numerical investigation of twelve large-scale concrete deep beams internally reinforced with GFRP bars without web reinforcement failed in shear which were experimentally tested and collected from literature. The collected specimens cover several parameters which usually influenced strength and behavior of deep beams as shear span/depth ratio, the reinforcement ratio, the effective depth, and the concrete strength. Concrete deep beams are generally analyzed using conventional methods such as empirical equations or strut and tie models. These methods however do not take into account the redistribution of forces resulting from non-linear materials' behaviors. To address this issue, non-linear finite element analysis that incorporates non-linear material behavior as ABAQUS package is used. It was found efficient in handling such analysis; the proposed simulation of the material in the present study is capable of predicting the real behavior of reinforced concrete deep beam reinforced with GFRP bars in terms of load–deflection behavior, failure load, failure mode, crack propagation, GFRP reinforcement strain, and concrete strain distribution, similar to the tested large scale deep beams.

Introduction

Corrosion of steel reinforcement in concrete structures leads to cracking and spalling of concrete, resulting in costly maintenance and repair. An innovative solution to such a problem can be provided by using fiber-reinforced polymer (FRP) as an alternative to steel reinforcement. FRPs are corrosion-free materials and have recently shown a great potential for use in structural applications because of their high strength-to-weight ratio. Therefore, replacing the steel reinforcement with

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Peer review under responsibility of Housing and Building National Research Center.

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http://dx.doi.org/10.1016/j.hbrcj.2015.02.006
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the non-corrosive FRP reinforcement eliminates the potential of corrosion and the associated deterioration. Extensive research programs have been conducted to investigate the flexural and shear behavior of slender (shallow) concrete members reinforced with FRP reinforcement [1]. Very little experimental data and nearly no finite element analysis exist for FRP-reinforced concrete deep beams. So, shear behavior of them has not been sufficiently understood.

The shear capacity of deep beams is a major issue in their design. The behavior of reinforced concrete deep beams is different from that of slender beams because of their relatively larger magnitude of shearing and normal stresses. Unlike slender beams, deep beams transfer shear forces to supports through compressive stresses rather than shear stresses. There are two kinds of cracks that typically develop in deep beams: flexural cracks and diagonal cracks. Diagonal cracks eliminate the inclined principal tensile stresses required for beam action and lead to a redistribution of internal stresses so that the beam acts as a tied arch. The arch action is a function of a/d (shear span/depth) and the concrete compressive strength, in addition to the properties of the longitudinal reinforcement. It is expected that the arch action in FRP reinforced concrete would be as significant as that in steel reinforced concrete and that the shear strength of FRP-reinforced concrete beams having a/d less than 2.5 would be higher than that of beams having a/d of more than 2.5 [2]. The application of the reinforced concrete deep beams within structural engineering practice has risen substantially over the last few decades. More specially, there has been an increased practice of including deep beams in the design of tall buildings, offshore structures, wall tanks and foundations. They differ from shallow beams in that they have a relatively larger depth compared to the span length. As a result the strain distribution across the depth is non-linear and cannot be described in terms of uni-axial stress strain characteristics [3]. Prediction of behavior of deep beams by design codes which contain empirical equations derived from experimental tests has some limitations. They are only suitable for the tests conditions they were derived from, and most importantly, they fail to provide information on serviceability requirements such as structural deformations and cracking. Likewise, the strut and tie model, although based on equilibrium solutions thus providing a safe design, does not take into account the non-linear material behavior and hence also fails to provide information on serviceability requirements. Cracking of concrete and yielding of steel are essential features of the behavior of concrete structures and, therefore, they must be taken into account in predicting their ultimate load capacity as well as service behavior. Failure to do so simply means that the redistribution of stresses in the structure is not taken into account [4]. Thus, the development of an alternative analysis method by FE is needed to understand its behavior. As reported by Enem et al. [4], finite element method (FEM) offers a powerful and general analytical tool for studying the behavior of reinforced concrete deep beams. Finite element method as a tool can provide realistic and satisfactory solutions for linear and nonlinear behavior of deep beam structural elements. Accordingly, it is very needed to generate reliable FE models that can be utilized to enhance the understanding of the fundamental structural response of the FRP-reinforced deep beams and hence optimize its design.

The main objective of this study was to investigate capabilities of the finite element simulation for further study on GFRP-reinforced concrete deep beam behavior instead of conducting expensive time consuming experimental works of large-scale structural elements.

Experimental technique

Characteristics of tested deep beams

Twelve concrete deep beams internally reinforced with GFRP bras were collected from literature [1]. They were constructed and tested to failure. The primary test variables included the a/d, the reinforcement ratio ρ, the effective depth d, and the concrete strength f_c'. The objective of the test program was to assess the design parameters that influence the strength and behavior of FRP-reinforced concrete deep beams without web reinforcement. The configuration of the specimens is given in Table 1 and Fig. 1. The a/d of the specimens were selected to cover a wide range of the deep beam category at the ultimate and equivalent serviceability limit states and to fill gaps in the limited experimental data available on FRP-reinforced concrete deep beams. Specimens were grouped into three series having nominal heights h of 300, 600, and 1000 mm. To study the effect of concrete strength on the shear capacity, both normal- and high-strength concretes were used. The reinforcement in all specimens consisted of GFRP bars, as this is the most commonly used FRP in the industry. The reinforcement ratios were selected such that the stress level in the FRP would not exceed approximately 25% of the specified tensile strength

Table 1 Characteristics of GFRP-Reinforced Concrete Deep Beams.

Specimen	ρ, %	Height (h), mm	Width (b_w), mm	Shear span (a), mm	a/d	Overhang length, mm*	fc', MPa
A1N	1.49	306	310	276	1.07	874	40.2
A2N	1.47	310	310	376	1.44	874	45.4
A3N	1.47	310	310	527	2.02	874	41.3
A4H	1.47	310	310	527	2.02	623	64.6
B1N	1.70	608	300	545	1.08	605	40.5
B2N	1.71	606	300	743	1.48	605	39.9
B3N	1.71	607	300	1040	2.07	605	41.2
B4N	2.13	606	300	736	1.48	814	40.7
B5H	2.12	607	300	736	1.48	614	66.4
B6H	1.70	610	300	1040	2.06	460	68.5
C1N	1.58	1003	301	974	1.10	826	51.6
C2N	1.56	1005	304	1329	1.49	821	50.7

Please cite this article in press as: I.M. Metwally, Three-dimensional nonlinear finite element analysis of concrete deep beam reinforced with GFRP bars, HBRC Journal (2015), http://dx.doi.org/10.1016/j.hbrcj.2015.02.006