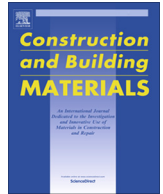




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Replacement of steel with GFRP for sustainable reinforced concrete

Shamim A. Sheikh, Zahra Kharal*

Department of Civil Engineering, University of Toronto, 35 St George St, Toronto, ON M5S 1A4, Canada

HIGHLIGHTS

- Existing tension stiffening models overestimate post-cracking stiffness in GFRP-RC beams.
- A newly proposed tension-stiffening model predicts the response of GFRP-RC beams much better.
- GFRP bars in monotonic compression can resist approximately 60% of the tensile strength of the bar.
- GFRP-RC columns display considerable amount of ductility and energy dissipation capacity.
- GFRP spirals can provide effective confinement until a strain of about 2%.

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ABSTRACT

Corrosion of steel in reinforced concrete structures has cost a significant amount of resources globally over the past few decades. Glass fiber reinforcement polymer (GFRP) bars present a feasible and cost-effective solution to the problem of steel corrosion. The aim of this paper is to let engineers gain a better understanding of the overall behavior of GFRP as internal reinforcement so that they have more confidence using it as a sustainable material. This paper provides a few significant outcomes from an extensive experimental program underway at the University of Toronto. The work discussed here provides a summary of the tests on 24 GFRP reinforced beams, 60 GFRP direct tension specimens and 20 GFRP confined columns, and evaluates the behavior of GFRP-RC in flexure, shear, tension and compression. A recently proposed tension-stiffening model has been incorporated in analytical modeling of GFRP-RC beams and the results show significant improvement in the prediction of deflection and stiffness of the beams. Results from column tests show that GFRP bars used as longitudinal reinforcement can resist compressive stresses in excess of 700 MPa and GFRP lateral reinforcement can confine concrete core more effectively than steel.

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1. Introduction

Engineers today are faced with a huge problem of deteriorating infrastructure world-wide. The main cause of deterioration among reinforced concrete structures is the corrosion of internal reinforcing steel. The total annual cost of corrosion worldwide in 2010 was estimated at USD \$2.2 trillion which amounts to about 3% of the world's GDP [1]. Glass fiber reinforced polymer, GFRP, bars have been introduced as a light-weight, corrosion resistant material which are a viable replacement for traditional steel reinforcing bars.

GFRP also remains one of the more cost effective FRP products commercially available with significant cost advantage over stain-

less steel. While research into internal GFRP bars has been ongoing over the last few decades, considerable progress was made in the past two decades specifically with the work of pioneering research carried out by groups such as ISIS Canada and resulted in several design recommendations and guidelines for designing GFRP reinforced concrete members, including the ACI 440-1R-15, CSA-S6-14 and CSA S806-12. Since then, GFRP bars have been used in various applications such as bridge decks and barrier walls; Hall's Harbor Wharf Bridge in Nova Scotia, Joffre Bridge in Quebec and Crowchild Trail Bridge in Alberta are some examples of Canadian bridges in which GFRP was used as the main reinforcement [2]. Despite these advances in the field of the GFRP-RC over the last few years, most designers are still reluctant to replace steel with GFRP as the main reinforcement in reinforced concrete members. This is primarily due to a lack of data and analytical procedures in this field compared with those available for conventional steel-reinforced structures.

* Corresponding author.

E-mail addresses: sheikh@ecf.utoronto.ca (S.A. Sheikh), zahra.kharal@mail.utoronto.ca (Z. Kharal).

Notations

β	tension stiffening factor	N	total tensile force carried the member
ϵ_{cr}	strain corresponding to concrete tensile cracking stress	f_c	maximum compressive concrete cylinder stress
ϵ_{cf}	net concrete tensile strain of the specimen	f_c	average concrete tensile strength after cracking
γ	factor based on surface profile of the reinforcing bar	f_t	uniaxial cracking stress of concrete
E_b	modulus of elasticity of reinforcing bar		

Although GFRP has many advantages over steel and is a viable reinforcement alternative, it presents its own challenges in terms of having very different properties than steel. Other than its lack of post-elastic behavior, the major shortcoming of GFRP is its relatively low stiffness in comparison with steel. The reduced stiffness results in deflections and crack-widths in GFRP-RC flexural members that are much larger than conventional steel-RC members. This results in GFRP reinforced concrete design being largely controlled by service conditions that makes it essential to predict the deflection in GFRP-RC members more accurately than for steel-RC members. The lower modulus of elasticity of GFRP can also adversely affect the shear response by widening cracks resulting potentially in a greater rotation of the diagonal principal compression strut thus reducing the efficiency of shear reinforcement.

While the hesitation to use GFRP-RC in reinforced concrete beams and slabs that depict flexural behavior has been addressed in literature to some extent, the compressive response of GFRP bars is mostly unexplored. Therefore, many design codes in North America such as ACI-440 [3] explicitly prevent designers from using GFRP bars in members under compression while CSA-S6 [4] does not have any provisions regarding this application. This is mostly due to the uncertainty in the response of GFRP bars in compression and a lack of sufficient data on the behavior of GFRP-RC columns. Additionally, the use of GFRP spirals offer a great solution to prevent the deterioration of the column cover due to reinforcement corrosion. The expansion caused by corrosion of steel spirals results in the spalling of concrete cover that results in a drop of load carrying capacity due to a smaller cross-section, and severely damages the structural integrity of the column due to loss of confinement. The repair and rehabilitation of such structures is extremely costly.

This paper aims at creating a better understanding of the overall behavior of GFRP as internal reinforcement. The research presented here is part of a large research program carried out at the University of Toronto investigating the behavior of GFRP in a variety of concrete structures. In one of the projects, Vint and Sheikh [5] investigated different bent, straight and anchored GFRP products for bond behavior. Getzlaf [6] investigated the flexural behavior of GFRP reinforced concrete, including the deformability of GFRP-RC beams, presenting new methods for evaluating member deformability. Johnson and Sheikh [7] studied the behavior of large concrete beams reinforced with GFRP bars and stirrups under flexure and shear. Kharal [8] investigated the deformation and serviceability characteristics of GFRP-RC beams and investigated the role of tension stiffening. This paper provides an overall view of the developments from this research. It also presents results on the behavior of columns for a better understanding of the application of GFRP bars in compression and GFRP spirals for confinement.

2. Experimental investigation and results

2.1. GFRP reinforced concrete beams

A systematic investigation was carried out to determine the influence of concrete strength, GFRP transverse reinforcement and longitudinal reinforcement stiffness on the behavior of beams

in flexure and shear. To this effect, a set of twenty-four large-scale GFRP reinforced beams were constructed and tested [7,9]. All the beam specimens had the same overall dimensions of 400 mm $\times$ 650 mm $\times$ 3650 mm and a longitudinal reinforcement ratio of 1%. The loading arrangement was a 3-point set-up with a constant shear span of 1680 mm. The bearing plates used were 150 mm wide resulting in a clear shear span of 1530 mm. Testing was conducted in a monotonic displacement controlled manner. The typical specimen geometry and test set-up can be seen in Fig. 1.

The deformability of the GFRP-RC beams was also investigated in a test program consisting of 15 GFRP-reinforced beams with section size one-half of that shown in Fig. 1 [6]. Deformability and performance in flexure has been a critical and often contentious topic regarding GFRP design. Ductility, as defined traditionally does not explain the behavior of GFRP-reinforced test specimens appropriately. However, from the load versus deflection responses of several beam tests (Fig. 2), it can be seen that GFRP-RC has the capacity to deform substantially which provides the ability to absorb energy. Hence, the lack of ductility in GFRP does not necessarily directly translate to brittleness. All the beams in Fig. 2 contained concrete that had a compressive strength of 32 MPa and bar Type C which had ribbed surface profile. NT, 22B, 40B and 50B in the names of the specimens indicate, respectively, no transverse reinforcement, 0.22%, 0.40% and 0.50% transverse reinforcement provided by bent bar stirrups. It was shown in the interpretation of test results [9] that the choice of transverse reinforcement has a significant impact on not only the flexural failure load but also the ultimate deflection of the beam. In fact, GFRP-RC beams with relatively lower shear reinforcement displayed visibly wider cracking prior to failure giving indication of failure. The research showed that GFRP-RC structures have the potential to be designed for a non-brittle failure.

The experimental beam results were simulated using nonlinear finite element analysis. The beam section was modelled in VecTor2 that is a 2-Dimensional nonlinear finite element analysis program [10]. The GFRP bond model developed by Vint and Sheikh [3] was adopted in VecTor2 to improve the accuracy of the predicted results. Fig. 3 shows the comparison of the analytical and experimental load versus deflection results of a normal and high strength concrete beam. When tension stiffening was not considered in the analysis (VT2 No Tension Stiffening), it resulted in very soft and unreasonable results. Similar results were observed for other beams. Hence, the study concluded that tension stiffening consideration is much more important in GFRP-RC members for deflection calculation than in steel-RC members due to the low stiffness of GFRP.

The beams were then analyzed in VecTor2 using Benz 2003 [11] tension stiffening model and Collins and Mitchell 1987 model [12] (Fig. 3). However, the differences between the measured and predicted deflections were still found to be considerable. Among all the steel-RC tension stiffening models tested, the Collins and Mitchell 1987 tension stiffening model was found to give comparatively better results for the GFRP-RC specimens. But even this model resulted in only minor improvements to the peak capacity and did not change the post-cracking stiffness. This is because this model does not consider the influence of reduced GFRP modulus

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