Safety of GFRP-Reinforced Concrete Columns Subjected to Sustained Intensity

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Abstract: This paper presents the safety of concrete columns reinforced with glass fiber reinforced polymer (GFRP) bars when subjected to sustained concentric loading. An analytical model is developed based on force equilibrium and strain compatibility alongside the time-dependent properties of constituent materials. The response of the columns is predicted up to a service period of 100 years. The implications of creep and shrinkage are noteworthy on the long-term behavior of the columns.

1. INTRODUCTION

Reinforced concrete columns are required to carry gravitational loads in buildings. During the service life of a frame structure, sustained loading occurs and vertical members experience elastic deformations. Typical examples of detrimental distress involve mechanical loading, creep, and shrinkage [1]. It is well recognized that the accurate prediction of time-dependent response of constructed columns is a challenging task since a number of factors are engaged at the same time, affecting the displacement of cementitious materials [2]. When concrete columns are situated in a corrosive region, corrosion damage is considered to be a critical problem. For this reason, the concrete engineering community frequently adopts epoxy-coated steel reinforcing bars to postpone the occurrence of corrosion. Nonetheless, concerns on long-term durability are not fully addressed and corrosion eventually takes place in those columns. An alternative approach has been proposed in the 1990’s using non-metallic reinforcement, which can fundamentally resolve those identified issues. Among many, glass fiber reinforced polymer (GFRP) reinforcing bars are predominantly employed around the world. The application of GFRP rebars has been broad from slabs to girders [3]; however, due to the conservative nature of structural design, their use was generally limited for columns [4]. Several researchers recently began investigating the potential of GFRP as a reinforcing material for vertical load-bearing members [5,6]. The ramifications of slenderness for GFRP-reinforced concrete columns were studied [7] and brittle-tension was found to be a critical failure mode. Some research projects examine the behavior of large-scale columns with GFRP rebars [4]: although the reinforcing material did not yield, a progressive reduction in stiffness was recorded and remarkable ductility was noted. A comparative study revealed that the axial capacity of columns reinforced with conventional steel and GFRP rebars was reasonably similar within a margin of less than 10% [8]. Regarding the ductility of GFRP-reinforced concrete columns, flexural stiffness played an important role [9].

The majority of existing research projects on GFRP-reinforced concrete columns have been concerned with short-term behavior [5,10]; for this reason, insufficient knowledge is available in the area of long-term response. This technical gap is significant since all constructed columns carry gravity loadings and many of them are exposed to sustained loadings. In this paper, the short- and long-term performance of concrete columns with GFRP rebars is examined through an analytical approach with an emphasis on concentric loading. A numerical parametric study is conducted to evaluate the behavior of those columns when variable properties are associated. Despite the possible use of GFRP as transverse ties, the focus of the current study is on its longitudinal application.

2. SIGNIFICANCE OF RESEARCH

The presence of sustained loading is imperative in constructed building structures. As such, both instantaneous and time-dependent responses are crucial topics to explore. This aspect is particularly important for GFRP-reinforced concrete columns because the composition of the composite material includes a polymeric resin that is susceptible to creep-type loading. In line with present research needs, the research attempts to understand the long-term behavior of columns with GFRP. The subject area is new and will impart necessary information to update published design guidelines [3], which will enhance the safety of structural members incorporating such non-conventional construction materials.

3. PREDICTIVE MODELING

3.1. Material Aspects

The time-dependent strain of concrete ($\varepsilon_c(t)$) may be expressed by

$$\varepsilon_c(t) = \varepsilon_e(t) + \varepsilon_{cr}(t) + \varepsilon_{sh}(t) \tag{1}$$

where $\varepsilon_e(t)$, $\varepsilon_{cr}(t)$, and $\varepsilon_{sh}(t)$ are the elastic, creep, and shrinkage strains, respectively. The elastic strain component is a function of instantaneous stress and the time-dependent elastic modulus of concrete, while the creep and shrinkage terms may be predicted using empirical equations specified in design documents [11,12]; for example,

$$\phi(t) = \frac{(t - t_0)^{0.6}}{10 + (t - t_0)^{0.6}} \phi_u \tag{2}$$

$$\chi(t) = \frac{t_0^{0.5}}{1 + t_0^{0.5}} \tag{3}$$

where $\phi(t)$ is the creep coefficient at time t; t_0 is the time at which the load is applied; ϕ_u is the ultimate creep (ϕ_u = 2.35); and $\chi(t)$ is the ageing coefficient. The time-dependent effective elastic modulus of GFRP at time t ($E_{fe}(t)$) may be obtained from

$$E_{fe}(t) = \frac{E_f(0)}{1 + \phi_f(t)} \tag{4}$$

where $E_f(0)$ is the initial elastic modulus of GFRP and $\phi_f(t)$ is creep coefficient of GFRP.

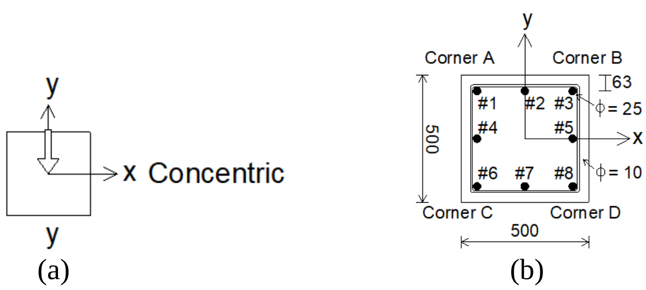

Figure 1: Column details: (a) loading scheme; (b) placement of GFRP reinforcing bars (unit in mm)

3.2. Short-Term Response

As depicted in Fig. 1(a), a square column was considered under concentric loading. By definition, the axial load (N) is expressed as

$$N = \int_A \sigma dA = N_c + N_f \quad (5)$$

where σ is the normal stress of the model section; A is the cross-sectional area of the column; and N_c and N_f are the axial resistance of the concrete and GFRP, respectively, which may be obtained by

$$N_c = \int_{A_c} E_c \varepsilon dA \quad (6)$$

$$N_f = \sum_{i=1}^{N_{fi}} A_{fi} E_f \varepsilon \quad (7)$$

where E_c and E_f are the elastic moduli of the concrete and GFRP, respectively; ε is the axial strain of the column; and A_{fi} is the cross-sectional area of the i^{th} rebar. Equation 5 can be re-written, as follows:

$$N = \left(E_c A_c + \sum_{i=1}^{N_{fi}} A_{fi} E_f \right) \varepsilon_0 \quad (8)$$

where ε_0 is the initial column strain.

3.3. Long-Term Response

The long-term strain of the column when subjected to sustained loading may be attained by combining Eq. 8 and Eqs. 9 and 10

$$J_{sh}(t) = E_e^{'}(t) A_c \varepsilon_{sh}(t) \quad (9)$$

$$J_{CR}(t) = E_c(0) \frac{\phi(t)(\chi(t) - 1)}{1 + \chi(t)\phi(t)} \quad (10)$$

where $E'_e(t)$ is the age-adjusted effective modulus at time t; $\varepsilon_{sh}(t)$ is the time-dependent shrinkage strain; and $E_c(0)$ is the initial elastic modulus of the concrete. Once the long-term strain is calculated, the column stress at time t ($\sigma_c(t)$) is determined

$$\sigma_c(t) = E_e^{'}(\varepsilon - \varepsilon_{sh}) + \frac{J_{CR}(t)}{E_c(0)} \sigma_c(0) \quad (11)$$

3.4. Validation

Figure 2 compares the predicted responses and experimentally measured data taken from literature. The behavior of two columns under concentric loading was excerpted from [5,10] and their normalized stress vs. strain and load vs. GFRP strain were studied. The model behavior was linear until failure occurred and good agreement was made within a typical service load range. It should be noted that the nonlinear post-peak responses logged in the test specimens were not calculated because the formulated model was reliant upon elastic theory.

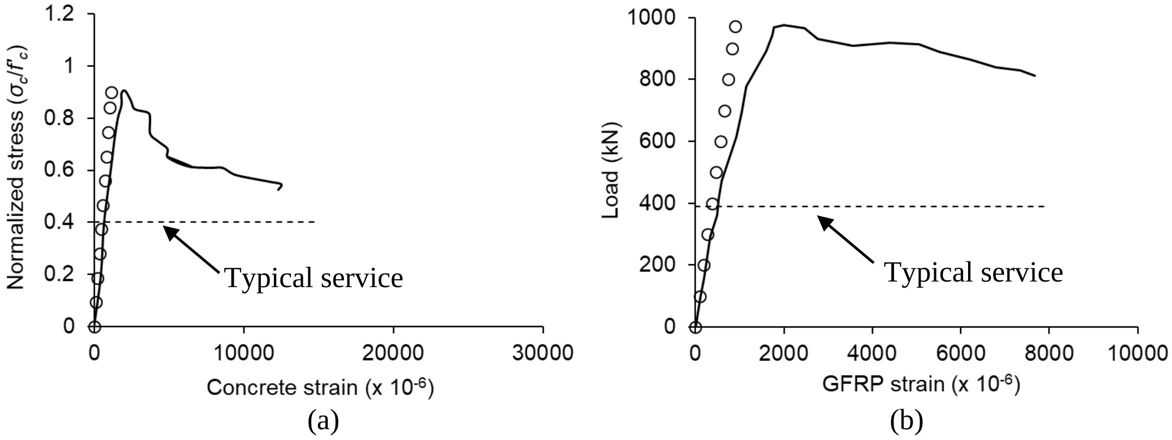

Figure 2: Validation of the proposed modeling approach: (a) normalized stress vs. strain [10]; (b) load vs. GFRP strain [5]

4. IMPLEMENTATION OF THE MODEL

4.1. Benchmark Column

The default column, taken from literature [13], was composed of a square concrete section (500 mm by 500 mm) and eight No. 8 GFRP reinforcing bars (Fig. 1(b)). The compressive strength of the concrete was f'_c = 35 MPa with an elastic modulus of E_c = 28 GPa, while the tensile strength and modulus of GFRP were f_{fu} = 1,030 MPa and E_f = 46 GPa at a rupture strain of ε_{fu} = 0.0224. For simplified loading, a typical service load level of 40%P_u (P_u = ultimate load) was assumed to be the sustained intensity.

4.2. Short-Term Response

Figure 3 exhibits the strains of the concrete and GFRP rebars under concentric loading: negative strains indicate compression. To represent a typical service state, the applied load level was set to 40%f'_c. Owing to a lack of eccentricity, the concrete strain of -106×10^{-6} was constant across the column section. It is, however, noted that when an eccentric load is applied, the strain profile will become irregular. The magnitude of the GFRP strain was the same as that of the concrete strain, which means strain compatibility was valid.

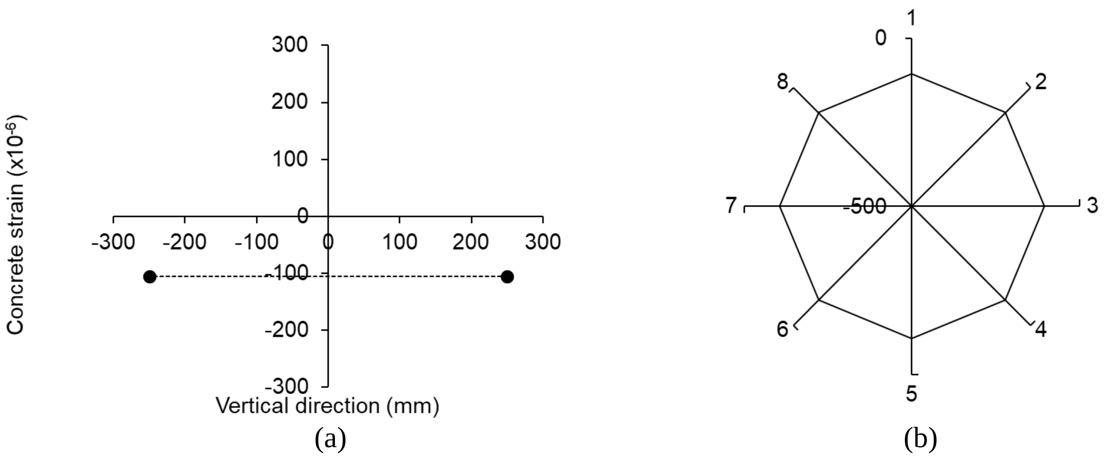

Figure 3: Short-term response of column: (a) concrete strain; (b) GFRP strain (numbers 1 to 8 indicate rebars)

4.3. Long-Term Response

4.3.1. Material behavior

Shown in Fig. 4 is a summary of the time-dependent material characteristics. The coefficient of creep in the concrete exponentially grew and, after about 5 years, it tended to be stable and approached the ultimate coefficient of 2.31 (Fig. 4(a)). The variation trend of the concrete shrinkage was analogous, as given in Fig. 4(b), and was less than 800×10^{-6} in compression. The stiff slope of the shrinkage was ascribed to the rapid development of hydration in the cement paste [2]. Figure 4(c) demonstrates the effective modulus of the concrete. Within a time frame of the first 65 days, a noticeable drop was predicted. The effective modulus of GFRP precipitously declined at an early age (Fig. 4(d)) and plateaued until 100 years.

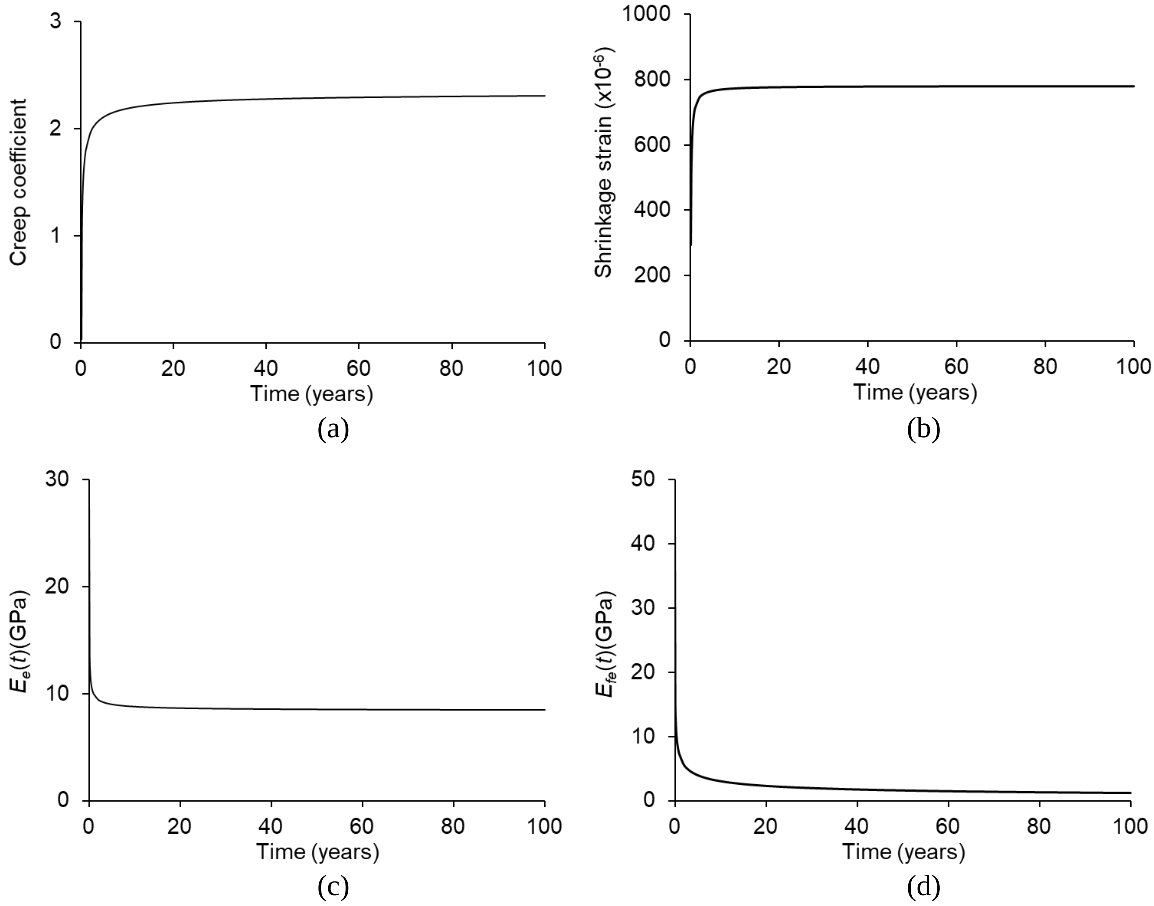

Figure 4: Long-term properties of constituent materials: (a) creep coefficient of concrete; (b) shrinkage of concrete; (c) effective modulus of concrete; (d) effective modulus of GFRP

4.3.2. Column behavior

The components of the long-term concrete strain detailed in Eq. 1 are illustrated in Fig. 5. For comparison, the strain components at the right-up corner are only visible. The elastic strain ($\varepsilon_e(t)$) was about 30% of the total strain ($\varepsilon_c(t)$)) at 100 years (Fig. 5(a)), indicating the amount of potential elastic recovery when the column was unloaded. The shrinkage strain component accounted for almost 70% of the total strain ($\varepsilon_{sh}(t)$), while the creep component ($\varepsilon_{cr}(t)$) was negligible (Figs. 5(b) and (c), respectively). As compared in Fig. 5(d), the shrinkage strain dominated the long-term response of the column.

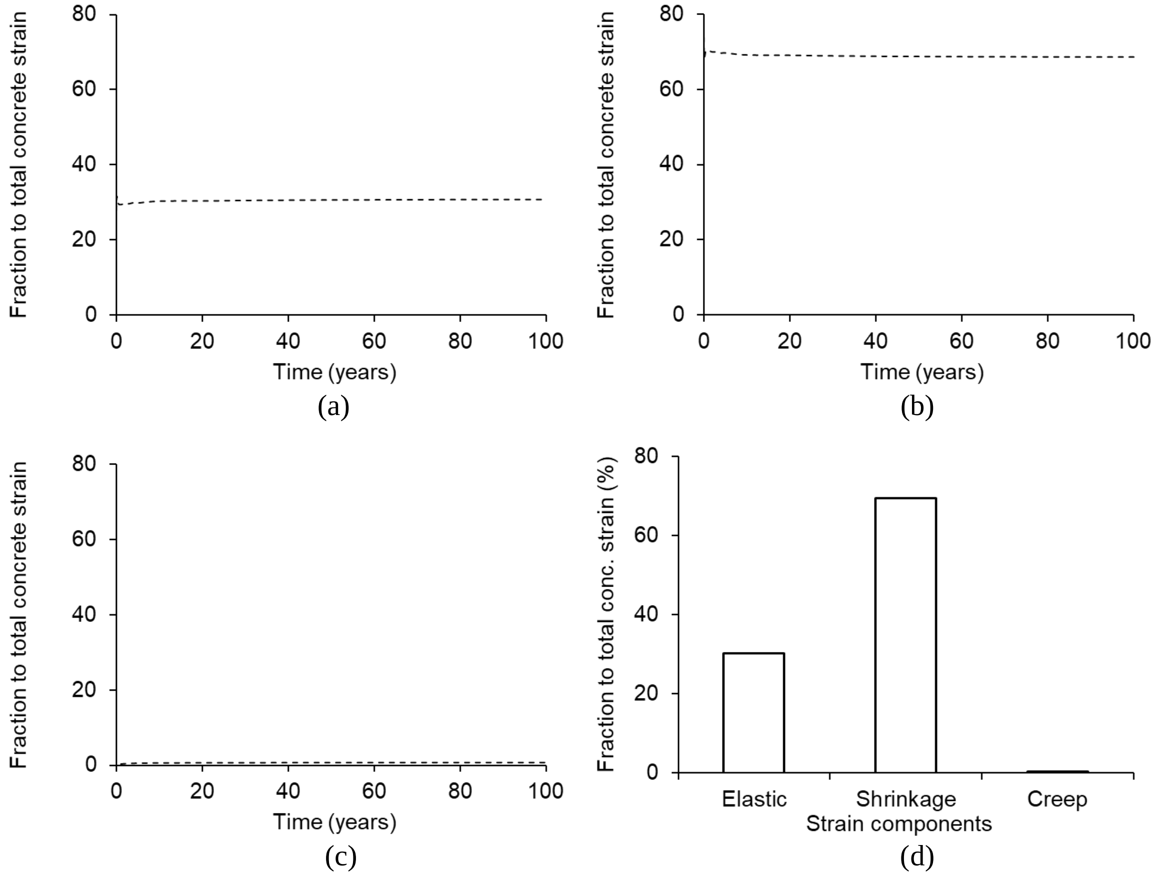

Figure 5: Time-dependent strain at the right-up corner of column: (a) elastic; (b) shrinkage; (c) creep; (d) average fraction spanning from 28 days to 100 years

4. CONCLUSION

This research has examined the safety of a GFRP-reinforced concrete square column under short- and long-term loadings. The analytical model used for investigations was formulated as per force equilibrium and strain compatibility in conjunction with time-dependent material characteristics up to 100 years. The short-term response of the column demonstrated that the stress level associated with service loading did not cause detrimental effects. The most notable component in the development of concrete strains resulted from shrinkage, while the contribution of creep strains was negligible.

Acknowledgements

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