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RESEARCH ARTICLE / НАУЧНАЯ СТАТЬЯ

Reinforcement of columns using different composite materials

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Abstract. The adoption in construction of composite materials made by combining two or more materials to produce a material with improved properties over the separate components has been steadily increasing over the past decades. In the past few years there have been advances in composite manufacturing technology, increased demand for sustainable and eco-friendly building materials, and the need for materials that are lightweight and easy for transportation. For these reason, architects and civil engineers incorporate composites into structural elements to achieve these desired goals and optimize the cost of construction. One of the most common composite materials that was introduced to the industry is fiber reinforced polymer (FRP), produced by combining fibers (carbon, glass, or aramid) with a polymer matrix (epoxy or polyester). FRP materials are lightweight, durable and corrosion resistant, which makes them ideal for use in a wide range of construction applications. This study aims to propose a comparison between four different methods as a viable solution to strengthen and reinforce column structures. The structural behavior of three different composite materials was investigated. One traditional concrete-steel column was tested in the experiment for comparison. The other three columns were reinforced using carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP) and stainless steel respectively. The obtained experimental results were analyzed, and comparison of three different systems of reinforcement for strengthening columns with composite materials was performed.

Keywords: composite materials, fibers, reinforcement, resin, matrix, strength, stiffness

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Армирование колонн с использованием различных композитных материалов

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Аннотация. Внедрение в строительство композитных материалов, изготовленных путем объединения двух или более материалов с целью получения материала, обладающего улучшенными свойствами, по сравнению с отдельными компонентами, неуклонно растет в течение последних десятилетий. За это время произошел прогресс в технологии производства композитов, увеличился спрос на устойчивые и экологически чистые строительные материалы, а также потребность в материалах, являющихся легкими и удобными для транспортировки. По этой причине архитекторы и инженеры-строители включают композиты в конструктивные элементы для достижения желаемых целей и оптимизации стоимости строительства. Одним из наиболее распространенных композитных материалов, представленным в промышленности, является армированный волокнами полимер (FRP), полученный посредством объединения волокон (углерод, стекло или арамид) с полимерной матрицей (эпоксидная смола или полиэстер). Материалы FRP легкие, прочные и устойчивые к коррозии, что делает их идеальными для использования в самых разных областях строительства. Исследование нацелено на то, чтобы сравнить четыре различных метода в качестве жизнеспособного решения для укрепления и усиления конструкций колонн. Изучено структурное поведение трех различных композиционных материалов. В эксперименте для сравнения испытана одна традиционная бетонно-стальная колонна. Остальные три колонны усилены с использованием углепластика, стеклопластика и нержавеющей стали соответственно. Полученные экспериментальные результаты проанализированы, выполнено сравнение трех различных систем армирования для усиления колонн композитными материалами.

Ключевые слова: композитные материалы, волокна, армирование, смола, матрица, прочность, жесткость

1. Introduction

Reinforcing column structures using composite materials like carbon fiber reinforced polymer (CFRP) or glass fiber reinforced polymer (GFRP) is a well-established solution in the construction field. The effectiveness of these reinforcement methods has been proven and validated by several experimental researches [1–3]. Fiber reinforced polymers offer several advantages over traditional reinforcement methods, such as high strength to weight ratio, design flexibility, and cost effectiveness. However, there are also some limitations associated with these materials. Although composite materials are slightly durable than traditional materials, they are prone to cracking, splitting, and delaminating especially exposed to high temperatures. The challenge to overcome these limitations has led to the development of new composite materials such as Fiber Reinforced Cementitious Matrix (FRCM) that consist of fibers in the form of meshes and grids combined with inorganic matrices to guarantee high performances in harsh conditions like high temperatures [4]. The effectiveness of CFRP and GFRP as an internal

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reinforcement for concrete columns have been investigated by several authors. In [5], Hany Tobbi investigated the behavior of concentrically loaded Fiber-Reinforced Polymer reinforced concrete columns with varying reinforcement types. The results showed that the ultimate axial strain of columns reinforced with FRP is almost 30% lower than those reinforced with the same volume of traditional steel. He also discovered that columns internally reinforced with a combination of steel longitudinal bars and FRP transverse reinforcements exhibit good gains in terms of compressive strength and ultimate axial strain [6; 7]. Stainless steel (SS) is another material for reinforcement that has been used for strengthening concrete structures due to its favorable durability and accessibility. In comparison to fiber reinforced polymers, stainless steel reinforcement is usually applied by means of mechanical connectors (without the use of resins) or embedded with lime mortars [8]; its degradation on the long-term is much slower comparing it to that of composite materials or traditional steel [9]. Its complete reversibility can often be achieved, and the isotropy of the stainless steel may represent a solution for multi-directional loading actions, typical for a structure subjected to static and dynamic loads [10; 11]. Although a lot of researchers have investigated structural behavior of these materials individually as reinforcement methods [12–15], there is not much data then in reinforcement of column. In this paper, four different reinforcement methods from CFRP, GFRP, stainless steel and traditional steel are compared. The structural behavior of each specimen is assessed, and the amount of reinforcement in each specimen is calculated.

2. Experimental investigation

This study is conducted through a combination of computation experimental methods in software ETABS 20. The mechanical properties of composite materials are determined by performing tensile, torsional and shear tests. Tests are conducted with different types of composite materials shown in Table 1 such as stainless steel, carbon fiber reinforced polymers (CFRP), and glass fiber reinforced polymers (GFRP). The results of these tests will be used to develop experimental structures for column reinforcement.

Properties of materials. For design and analysis the following SI codes were used:

– IS 456:2000 for reinforced cement concrete;

– IS 875.1:1987 for dead load assignment;

– IS 875.2:1987 for live load assignment;

– IS 875:1987 for wind load assignment;

– ACI 440.1.06 Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars.

In this experiment M30 grade concrete is used as a binding material along with different types of reinforcing bars (Table 2).

Table 1

Mechanical properties of different reinforcing materials

Properties	Steel bar	Stainless steel	GFRP	CFRP
Variant	HYSD 415	Austenitic (304)	E-class	Woven include epoxy
Specific mass density, gm/cm^3	7.8	8	2.1	1.8
Modulus of elasticity, GPa	200	190	51	500
Yield strength, MPa	415	205	N/A	N/A
Tensile strength, MPa	485	515	1500	3400
Thermal expansion coefficient, (C^o)$^{-1}$	$11.7\cdot10^{-6}$	$17.3\cdot10^{-6}$	$10\cdot10^{-6}$	0

Table 2

Mechanical properties of M30 grade concrete

Parameter	Unit	Values
Specific mass density	Kg/m^3	2548.53
Modulus of elasticity E	MPa	27386.13
Poisson's ratio	–	0.2
Thermal expansion coefficient	(C^o)$^{-1}$	0.000013
Shear modulus G	MPa	11410.89

3. Analysis

Tensile analysis. During the test, the load and the corresponding deformation was measured to determine the stress-strain behaviour of the material. The test results determined the ultimate percentage of rebar required to resist the load, elongation, and other mechanical properties of the material (Figure 1). To perform a tensile test of a rebar, the first step was to create a finite element model of the specimen. Here four specimens were created as a RC column of having cross section 450×450 mm^2 and height of 3 m each. Each specimen consists of four different types of rebar (Figure 2).

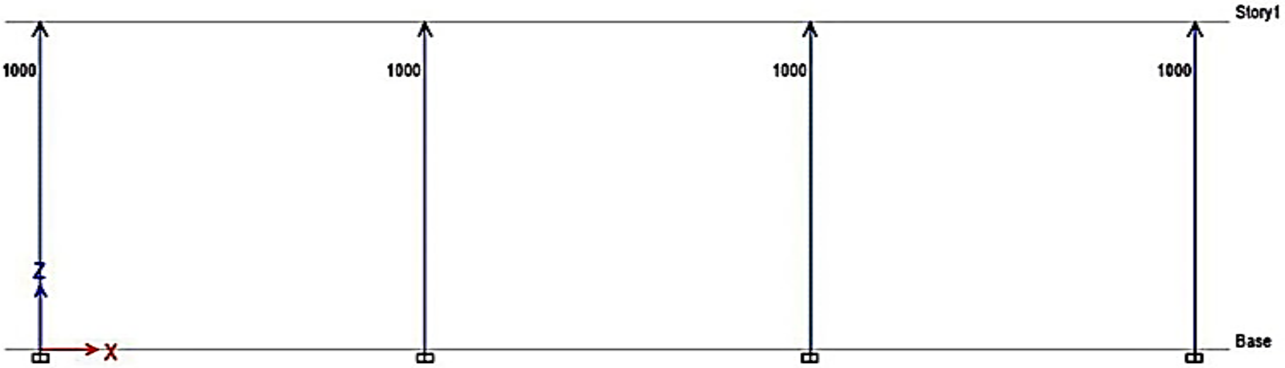

Figure 1. A model to analyze tension reinforcement in column

Figure 2. A model to analyze shear reinforcement in column

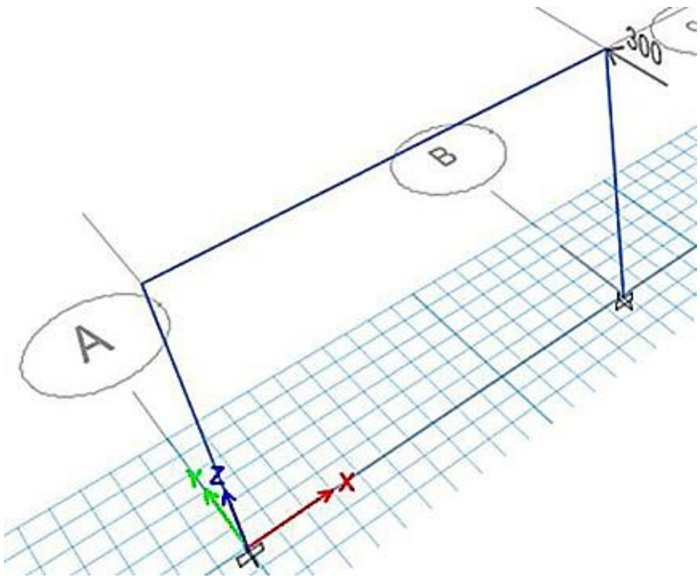

Figure 3. A model to analyze flexural reinforcement

Four different specimens made of HYSD415, austenitic stainless steel, GFRP and CFRP from left to right were subjected under a tensile load of 1000 kN and each column was meshed with enough nodes and elements to accurately capture the deformation and stress distribution of the specimen. As the load was applied, the deformation of the specimen was recorded, and the corresponding stress was calculated using the cross-sectional area of the rebar.

Shear analysis. During this test, the rebars are subjected to a force perpendicular to the longitudinal axis until failure, with the results indicating the rebar's resistance to shear forces. Four single story RCC bays measuring 3 m in height and 4 m in width. Each bay made with M30 grade concrete and HYSD415 steel, austenitic stainless steel, GFRP and CFRP reinforcement respectively. A 500 kN horizontal load is applied as shown below. After applying load, the required reinforcement is calculated and compared among each variant.

Torsional analysis. In this test four single story RCC bays are made. Each bay is made with M30 grade concrete and HYSD415 steel, austenitic stainless steel, GFRP and CFRP reinforcement respectively. A 300 кN horizontal load is applied as shown in the Figure 3.

4. Results

From the tensile test analysis, the results presented in Figure 4 were obtained.

Figure 4. Percentage of tensile reinforcement in different types of columns

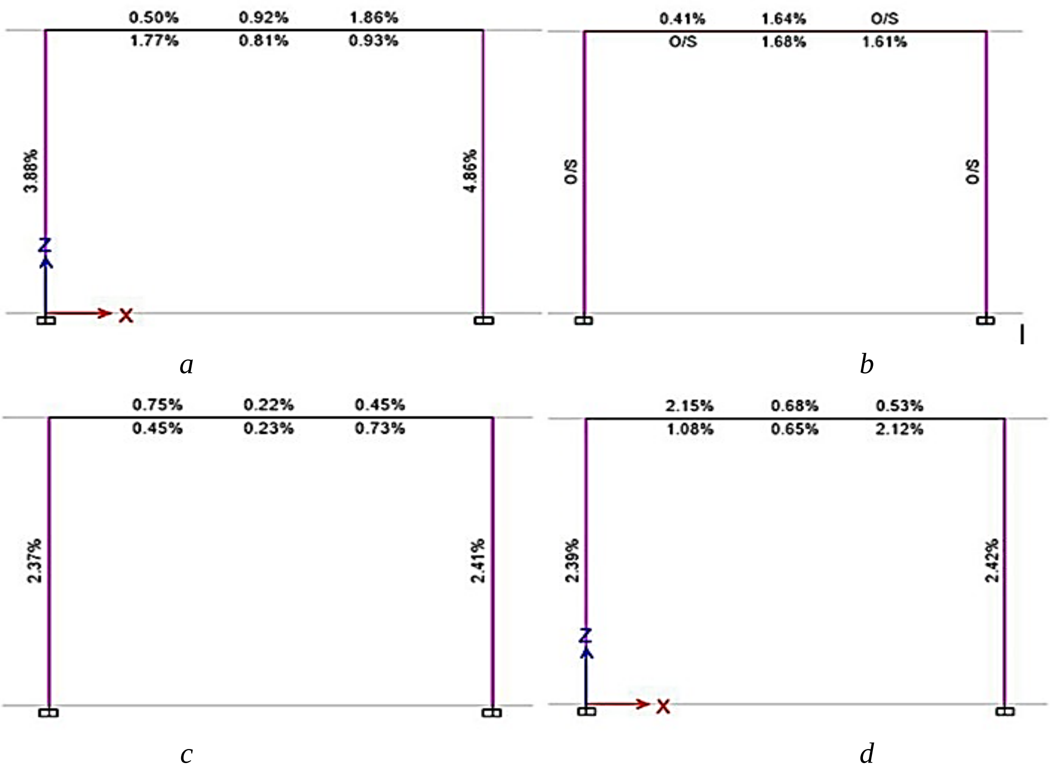

Figure 5. Variation of reinforcement of steel:
a – stainless steel; *b* – GFRP; *c* – CFRP; *d* – in shear

The diagram in Figure 1 presents information regarding the arrangement of columns and loads. By referring to Figure 4, it is illustrated that to withstand a tensile load of the same magnitude, traditional steel (HYSD415) necessitates 1.65% of the total cross-sectional area, whereas stainless steel, GFRP, and CFRP require only 3.14, 0.8, and 0.8% respectively. This disparity can be attributed to their varying ability to handle tensile stress.

From the shear test analysis, the results presented in Figure 5 were obtained.

Figure 1 was analyzed, and the outcomes have been displayed in Figure 4. Based on these findings, it can be deduced that to withstand a shear force of 500 кN, the column's steel percentage should be higher than that of GFRP and CFRP columns. However, for composite columns made of stainless steel, they failed or became over-stressed (o/s), indicating that the cross-sectional area of that column must be increased.

From the torsion test analysis, the results presented in Figure 6 were obtained.

In Figure 2 the 300 kN load was applied on right beam column junction so as per moment frame mechanism a 300·4 = 1200 kNm torsion will be applied on left column. To resist that torsional force every composite column, made up with different reinforcing materials requires different percentage of reinforcement (shown in Figure 6).

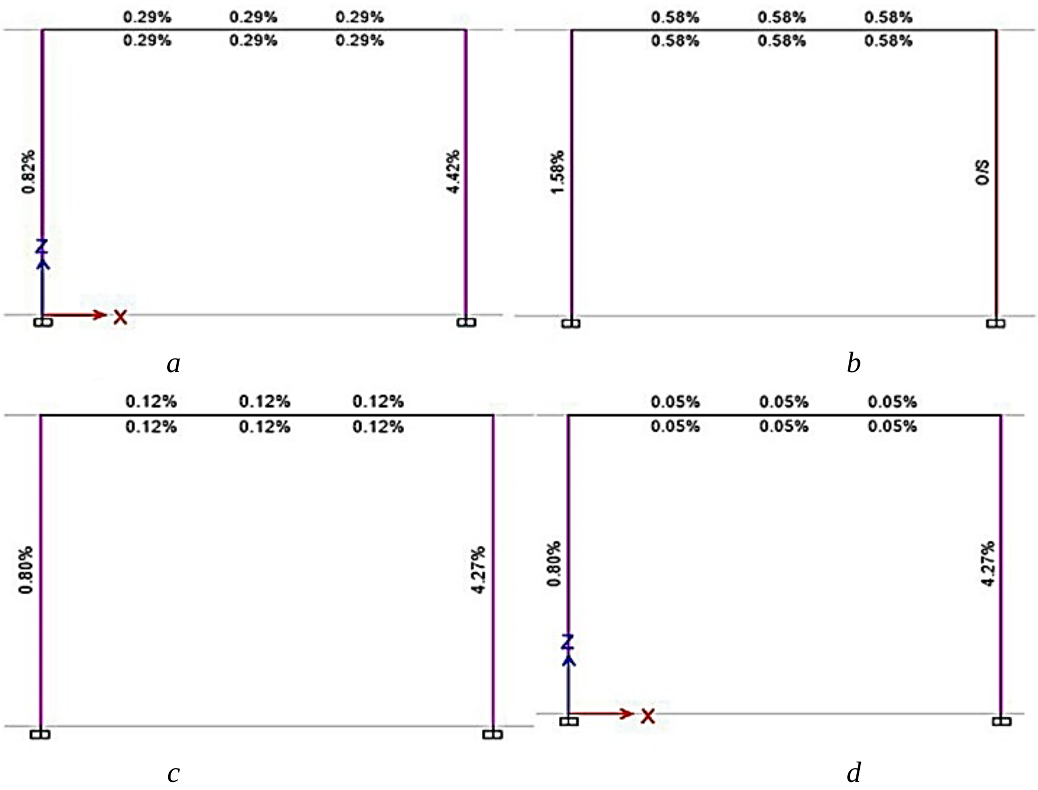

Figure 6. Variation of reinforcement of steel:
a – stainless steel; *b* – GFRP; *c* – CFRP; *d* – in torsion

From the result, stainless steel column requires more percentage of steel that other three columns as flexural stiffness is less than steel, CFRP and GFRP.

5. Conclusion

Table 3 presents the comparison of different types of reinforcement materials, namely steel, stainless steel, GFRP, and CFRP, based on their percentage of reinforcement on the left and right columns of a structural element.

Table 3

Deviation in percentage of reinforcement

Type of reinforcement	Left column, %	Right column, %	Average, %	Deviation w.r.t steel
Steel	3.88	4.86	4.37	0
Stainless steel	o/s	o/s	N/A	N/A
GFRP	2.37	2.41	2.39	–1.98
CFRP	2.39	2.42	2.405	–1.965

From the results obtained:

– the average percentage of reinforcement is found to be the highest for steel, followed by GFRP and CFRP, i.e. to withstand the same amount of load, the amount of steel reinforcement required would be more than that of GFRP and CFRP;

– the deviation with respect to steel is for GFRP and CFRP, which shows that these materials are 1.98% and 1.965% lower than steel, respectively. This analysis can be helpful in selecting the appropriate reinforcement material for a particular application, considering the mechanical properties, cost, and other factors;

– the combined cross-sectional area of two columns, each measuring 450×450 mm^2, is 0.45m^3. As a result, if GFRP and CFRP are utilized, the amount of reinforcement can be reduced by 1.98 and 1.965% respectively. This implies that when dealing with a substantial amount of concrete, the amount of reinforcement required will be considerably reduced;

– regarding beams subjected to direct compressive stress of 500 kN, the composite beam with GFRP showed superior performance, as it required a smaller amount of rebars, followed by the steel and CFRP composite beams. However, in the case of stainless steel, the top and bottom reinforcement were unable to withstand the stress. This discrepancy in percentage can be attributed to the differences in yield stress among various types of rebars.

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