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Evaluating the plasticity of concrete beam-column connections reinforced with FRP composite rebars

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ABSTRACT

Moment frame connections have high share to withstand deformation caused by earthquakes. Hence, connections of reinforced concrete structures must have sufficient plasticity in addition to resistance. Observations after earthquakes and the results of tests prove that structural damages have been more observed in the connections area. Implementation of reinforcement in limited volume of connection area is difficult and hence improving the behavior of the connection areas has been among the major issues discussed in structural engineering. In addition, corrosion in the bad environmental conditions is one of the main difficulties in implementing steels in concrete arming. Among alternative materials, FRP rebars that have higher durability, were given attention in recent years. In this study, the behavior of the element has been compared in these conditions by modeling the connection area with steel and FRP rebars.

1. Introduction

FRP is one of the fiber reinforced composite materials composed of two parts of fiber or reinforced fiber that are confined by a resin matrix of polymer. Generally, using steel rebars in structures that are exposed to salt or severe corrosion such as offshore structures, piers and bridge deck has been very disturbing due to the corrosion of steel and concrete degradation (Shayanfar et al. 2015a,b). Recent researches investigated the effect of steel rebar corrosion on the reduction of concrete compressive strength and coefficients of the compressive strength reduction was modified using the correlation of Vecchio and Collins (Ghanooni-Bagha et al. 2016, Shayanfar et al. 2016). Moreover, various methods such as using high-performance concrete and cover with high thickness, galvanized coatings, polymer-impregnated concrete, epoxy coatings and FRP polymer fibers have been suggested in recent years to improve failures. Using FRP polymer fibers is one of the most effective methods to increase the capacity and flexibility of concrete columns and beams. Extensive investigation has been done over the past two decades to repair and strengthen the reinforced concrete (RC) with polymer fibers (FRP), and behavior of the stress-strain confined by FRP has been studied (Abbasnia & Ziaadiny (2010), Abbasnia

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et al. 2012a,b, 2013, Nilson 1997; Meinheit & Jirsa 1981). But in the meantime, the use of FRP rebars, especially the rebars made of glass materials has been spread due to economic efficiency, mechanical strength and excellent corrosion. Also, due to the non-magnetic properties, the use of FRP rebars is recommended in structures under the influence of electromagnetic fields such as reactors, runways, MRI units in hospitals and laboratories. FRP rebars are around 75 percent lighter than conventional steel rebars. This decrease in density can lead to lower shipping cost, easy material relocation as well as reduction of the structure dead load due to reinforcement (Ehsani & Wight 1982).

Abrams (1987) carried out a research on the behavior of reinforced concrete connections. This researcher analyzed 18 laboratory samples under reciprocating lateral loads including small, medium, and large scales. Ehsani and White (1982) published their research on the behavior of external reinforced concrete connections under earthquake loads. Soroushian et al. (1988), in an experimental study, examined the behavior of bent rebars stretching out through their external connections. This researcher examined seven laboratory samples and variable parameters among these samples were rebars diameter, the confinement of connection concrete and concrete compressive strength. In 1990, Russo et al. (1990) published a work about relationship between adhesion and slip of reinforcements in reinforced concrete connections. Pantazopoulou and Bonacci (1992) responded also to questions about the reinforced concrete connections in their analytical studies. Ha et al. (1992) investigated the behavior of the connections made with high-resistance concrete against reciprocating loads. Studying the response of these connections, developing a new approach to design them, and evaluating the energy absorbed in them were among the main objectives of the study. In a laboratory research on the connections made with one by one scale, Luo et al., (1994) investigated the details of tensile reinforcement in connections of reinforced concrete frame corner. Scott and coworkers (Scott 1996, Hamil et al. 2004) were also among researchers that have conducted studies on the connections. Their studies can be divided into two parts(i.e. laboratory works and building a finite element model suitable for computer modeling of external connections). A notable point in this research is modeling of reinforcement inhibitory slip using unarmed elements of the concrete elements and extensive elements of the reinforcement. Hegger et al. (2003,2004) presented a new model for calculating shear resistance of external beam-to-column connections which were calibrated using the results of 200 experiments. This model considers the main parameters affecting shear strength as follows: connection slimming, column reinforcement ratio, concrete compressive strength, the type of containment of beam longitudinal reinforcement, and the amount and arrangement of connection shear reinforcement. They also employed ATENA finite element program for modeling and nonlinear analysis of middle and external beam-column connections.

Plasticity in structures in energy dissipation by plastic deformations can be the most important factor in avoiding severe damage failure during earthquakes. The main origin of plasticity is the ability of materials to withstand plastic strains without reducing attention to the tension. In this study the behavior of reinforced concrete beam-column connection is investigated numerically for two models with steel and GFRP rebars and some parameters such as the ultimate strength of the connection, the energy absorption and plasticity is computed and analyzed.

2. Consumable materials

2.1. FRP rebars

The mechanical behavior of FRP composite rebars is different from the behavior of steel rebars. Therefore, the philosophy of concrete building design with the use of FRP composite rebars is different from the steel rebars. Steel rebars have an almost isotropic behavior, but FRP composite rebars are anisotropic and have superior properties (high-tensile strength) only in the original fiber direction. In addition, FRP composite materials have linear elastic behavior, and do not show flowing behavior (entering a phase of plastic) such as steel. FRP composite rebars are non-electric and non-magnetic, and are resistant against corrosion. Using FRP composite rebars, we can avoid electromagnetic interference problems and corrosion of the steel. In addition, high tensile strength of composite rebars is a suitable alternative for use in tensile sections in concrete. The last type i.e. the GFRP composite rebar is cheaper than other types and is more common than other types of FRP composite rebars. Since the early 1960s, with the spread of the construction of offshore structures and major bridges that are exposed to sea water and corrosive environmental conditions, the researchers have sought to fix the steel corrosion and rusting which are the biggest defects of metal reinforced sheets (Nannil et al. 1996).

2.2. Concrete

Concrete Damage Plasticity model in ABAQUS software is used to simulate the behavior of concrete materials in concrete or compound models. In the concrete as in the steel, elastic and plastic properties of steel need to be defined. In the case of elastic properties, as in the steel materials, modulus of elasticity (E), Poisson's ratio (v) and density (ρ) are as presented in Table 1.

Table 1. Elastic properties of steel

Mass Density (kg/m^3)	**Young's Modulus (Pa)**	**Poisson's Ratio**
2400	31622776601.6838	0.15

The relation below was used to calculate the elastic modulus of concrete:

$$E_c = 5000\sqrt{f_c}, \tag{1}$$

where f_c is the compressive strength of concrete.

3. Numerical analyses

Since connections, as the most important and most vulnerable elements of structure, play an important role in plasticity, and given that the strength and plasticity of connections are largely dependent on specifications of rebars, in this part of research using ABAQUS software, we evaluated the performance of FRP rebars in concrete beam-column connection and its plasticity, compared with steel rebars.

3.1. Model of connection with steel rebar

Figs. 1 to 3 presents the contours of analyzed numerical results for plastic strain in concrete, von-mises stresses in the steel reinforcement and concrete, respectively.

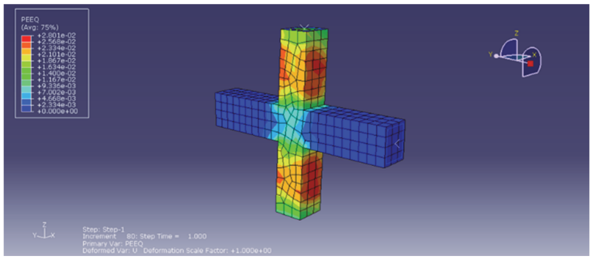


Fig. 1. Contour of plastic strain values in concrete containing steel reinforcement

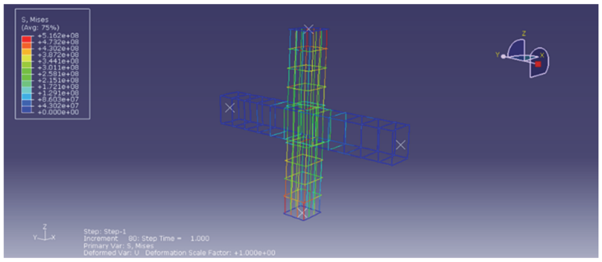


Fig. 2. Contour of Von Mises stress in steel reinforcements

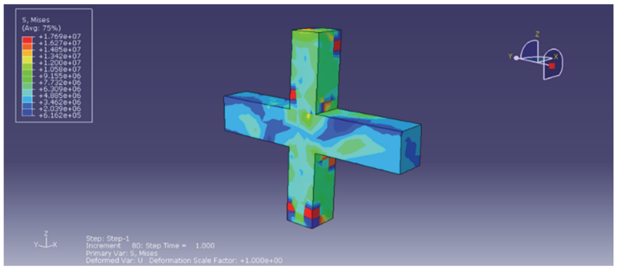


Fig. 3. Contour of Von Mises stresses in concrete reinforced with steel

3.2. Model of connection with GFRP rebar

In this section, simulation results for the use of GFRP rebar are presented and investigated. Figs. 4 to 7 shows the results of contours obtained for plastic strain, von-mises stresses in the steel reinforcement and concrete, respectively.

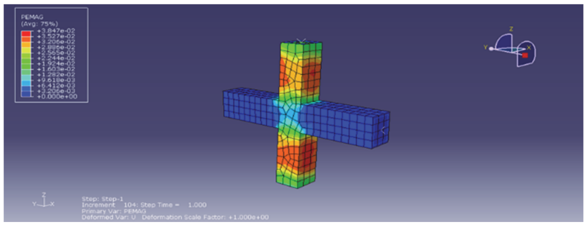


Fig. 4. Contour of plastic strain values in concrete containing GFRP reinforcement

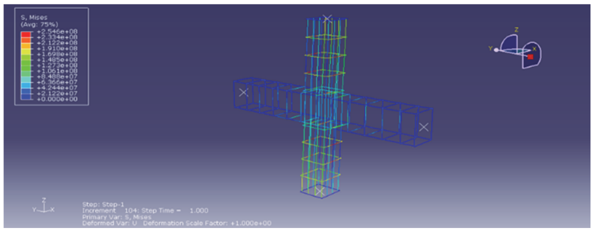


Fig. 5. Contour of Von Mises stress in GFRP reinforcement

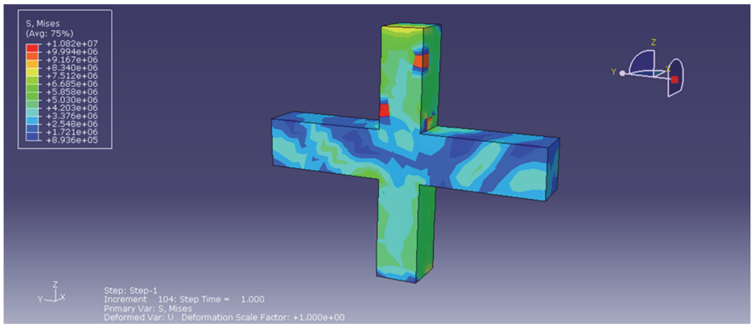


Fig. 6. Contour of Von-mises stress in concrete reinforced with GFRP

4. Results and Discussion

4.1. Ultimate strength of connection

The ultimate strength of connection is equal to the force obtained in the maximum drift (5%) which is equivalent to the displacement of the column end as much as 0.1 meters. To compare the connections with steel and GFRP rebars, drift-force graphs for these two connections are shown in Fig. 7. Based on the graph of comparing the ultimate strength in two steel and GFRP connections shown in Fig. 8, it can be seen that replacement of steel reinforcements with GFRP reinforcements reduced the ultimate strength of the connection. The observed reduction is 55%.

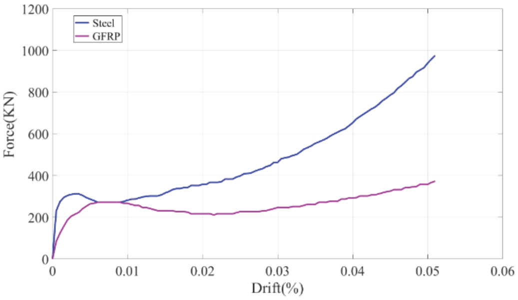
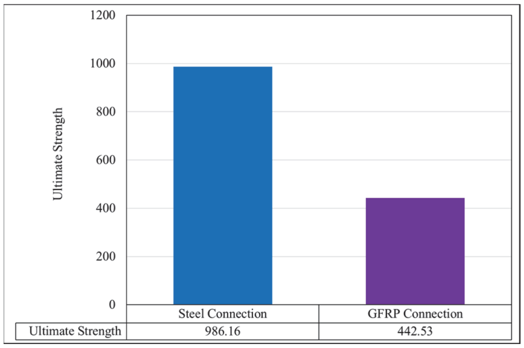


Fig. 7. Comparing the relative load-displacement curve in two cases of steel and GFRP rebars



	Steel Connection	GFRP Connection
Ultimate Strength	986.16	442.53

Fig. 8. Comparing the ultimate strength in two Steel GFRP connection

4.2. Connection plasticity

Displacement plasticity (μ_Δ) is the ratio of displacement in the final load (Δ_{max}) to the displacement at the first point that the tensile steel flows (Δ_{y}). It is calculated using the following equation:

$$\mu_\Delta = \frac{\Delta_{\mathrm{max}}}{\Delta_{\mathrm{y}}} \; . \tag{2}$$

According to the modelings (as typically shown in Fig. 9 for one of the connections), the steel plasticity ratio is 12.8, and plasticity ratio of connection with FRP rebars is 5.85 (see Fig. 10). According to the comparison of plasticity in two steel and GFRP connections, using GFRP reinforcements leads to a decrease in connection plasticity. This reduction is equal to 54%.

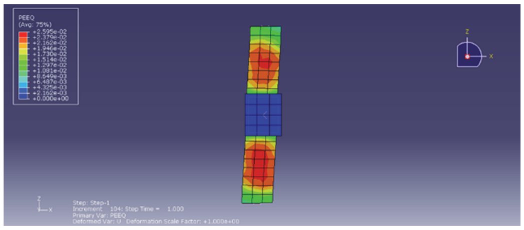


Fig. 9. The mode of connection core failure in GFRP reinforcement

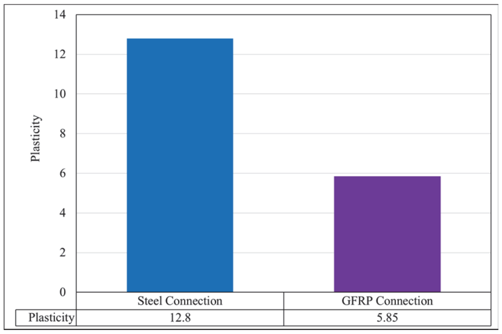


Fig. 1. Comparison of Plasticity in two steel and GFRP connections

4.3. The amount of connection energy absorption

Energy absorption capacity of connection depends on the area under the curve of load-displacement after each loading cycle, and this area is indicative of the importance of connection in seismic loading. When this area is bigger, absorbing more energy exerted on the structure at the time of earthquake, the connection prevents the destruction of structures. Therefore, the seismic behavior of connection becomes more suitable.

By comparing the time history curve of the total energy in two steel and GFRP rebars as presented in Fig. 11, it can be seen that the total energy change in GFRP connection is more uniform than the connections with steel reinforcements. Since the steel has a plastic behavior, by entering a non-linear phase, a sudden increase in the total energy is triggered.

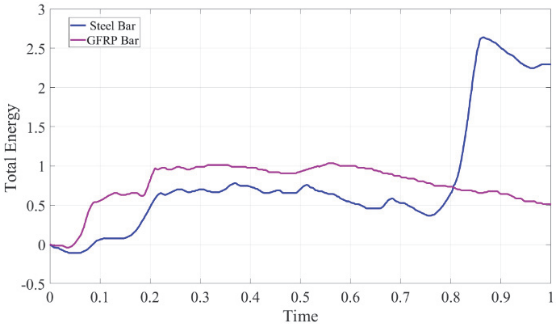


Fig. 2 Comparing the time history curve of the total energy in two steel and GFRP rebars

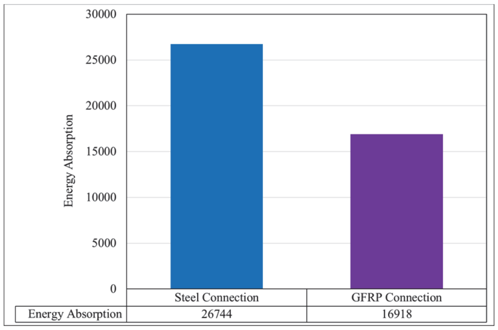


Fig. 3 Comparing the amount of energy absorption in two steel and GFRP connections

The amount of energy absorption in two connections with steel and GFRP reinforcements has also been compared in Fig. 12. According to this Figure it is concluded that the section with steel reinforcement can produce a higher plasticity. Plasticity reduction in the case of using GFRP rebars is equal to 37%.

4.4. The effect of increased percentage of the beam section arming

In this section, the effect of section reinforcement on the desired parameters has been considered. For the modelings done in the previous section, the percentage of section arming was equal to 0.57% (4 reinforcements with a diameter of 16 mm in cross-section of 40 × 35). Continuing with changes in the value, the impact on the ultimate strength and plasticity is displayed.

A) Mode 1

In this mode of modeling, the arrangement in the beam reinforcement has been used. The graph of ultimate strength and plasticity for this mode is shown in Fig. 13. Comparison of the ultimate strength values in the first mode (4 rebars with diameters of 14 mm) shows that the use of steel reinforcement leads to an increase of 50% in the ultimate strength compared to the GFRP reinforcement. Comparison of the plasticity values in the first mode (4 rebars with diameters of 14 mm) shows that the use of steel reinforcement leads to an increase of 50% in the plasticity compared to the GFRP reinforcement (see Fig. 14).

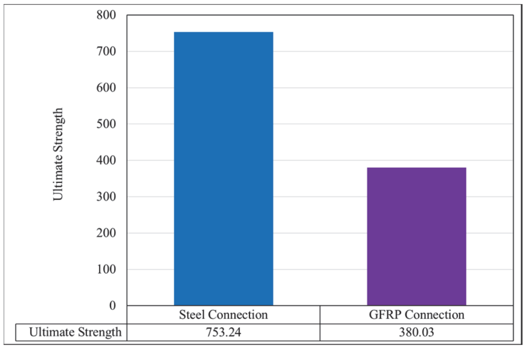


Fig. 4 Comparing the ultimate strength values in the first mode

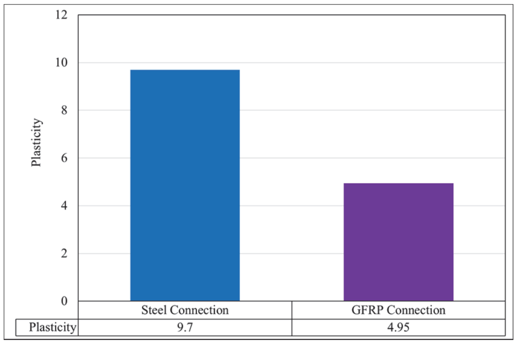


Fig. 5 Comparing the plasticity values in the first mode

B) Mode 2

In this type of modeling, the arrangement of 4Ø16 (i.e. 4 rebars with diameters of 16 mm) was used in beam reinforcement. The graph of ultimate strength and plasticity for this mode is shown in Figs. 15 and 16, respectively. Comparison of the ultimate strength values in the second mode (4 rebars with diameters of 16 mm) shows that the use of steel reinforcement leads to an increase of 55% compared to the GFRP reinforcement.

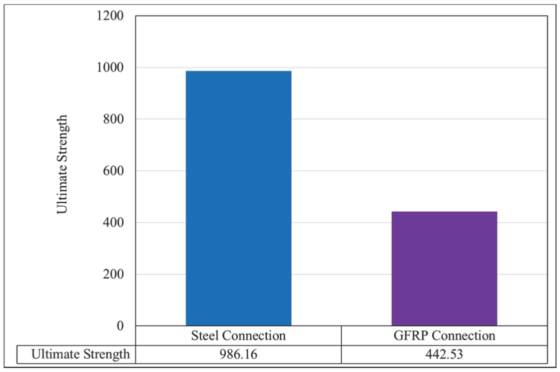


Fig. 6 Comparing the values of ultimate strength in the second mode

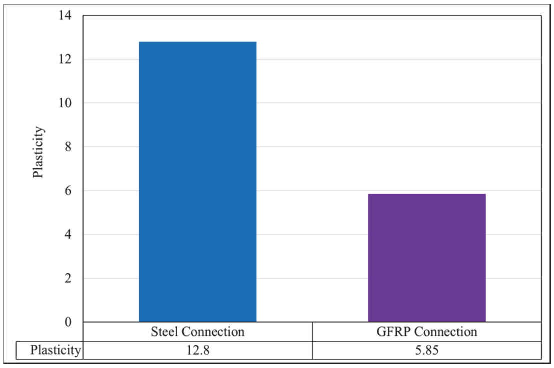


Fig. 7 Comparing the values of plasticity in the second mode

Comparison of the plasticity values in the second mode (4 rebars with diameters of 16 mm) shows that the use of steel reinforcement leads to an increase of 54% compared to the GFRP reinforcement.

C) **Mode** 3

In this type of modeling, the arrangement of 4Ø18 is used in beam reinforcement. The results of ultimate strength and plasticity for this mode are shown in Figs. 17 and 18, respectively. Comparison of the ultimate strength values in the third mode (4 rebars with diameters of 18 mm) shows that the use of steel reinforcement leads to an increase of 55% compared to the GFRP reinforcement. Comparison of the plasticity values in the third mode (4 rebars with diameters of 18 mm) shows that the use of steel reinforcement leads to an increase of 54% compared to the GFRP reinforcement.

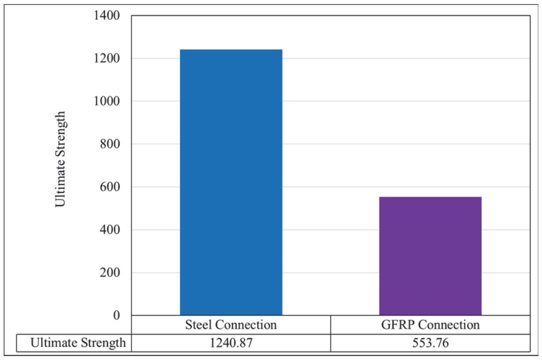


Fig. 8 Comparing the values of ultimate strength in the third mode

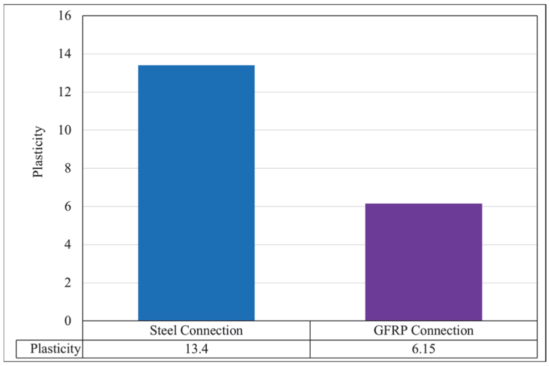


Fig. 18. Comparing the values of plasticity in the third mode

Mode 4

In this type of modeling, the arrangement of 4Ø20 is used in beam reinforcement. The graphs of ultimate strength and plasticity for this mode have been compared in Figs. 19 and 20, respectively. Comparison of the ultimate strength values in the third mode (4 rebars with diameters of 20 mm) shows that the use of steel reinforcement leads to an increase of 58% compared to the GFRP reinforcement. Comparison of the plasticity values in mode 4 (four rebars with diameters of 20 mm) shows that the use of steel reinforcement leads to an increase of 37% compared to the GFRP reinforcement.

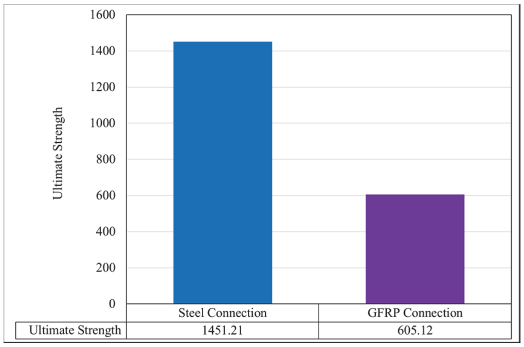


Fig. 19. Comparing the values of ultimate strength in the fourth mode

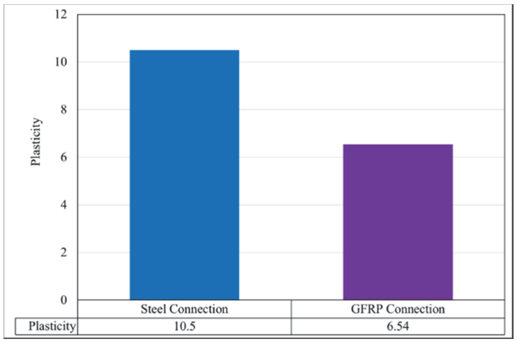


Fig. 20. Comparing the values of plasticity in the fourth mode

Summary of the results and the comparison between the values of the ultimate strength and plasticity for the four models with different arming percentages is provided in the following graphs (see Figs. 21 to 24).

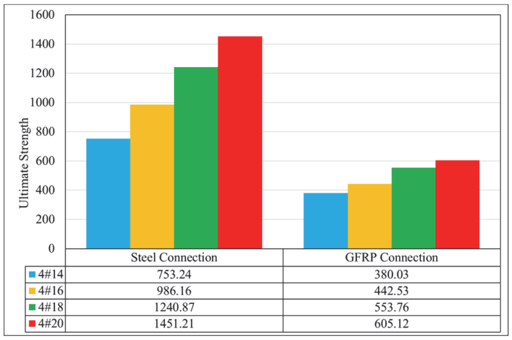


Fig. 9 Comparing the values of ultimate strength in steel and GFRP composite connections

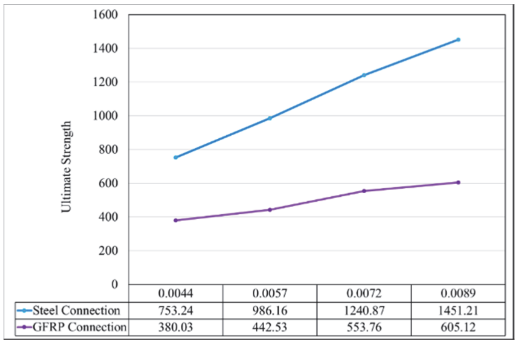


Fig. 10 The trend of ultimate strength changes in steel and composite connections based on the percentage of section reinforcement

Increasing the percentage of reinforcement in the beam section in the case of using steel rebars leads to increased connection ultimate capacity. By increasing the percentage of beam steel from 0.0044 to 0.0089 (2-fold increase), the connection ultimate capacity had an increase of 93%. Increasing the percentage of reinforcement in the beam section in the case of using GFRP rebars leads to increased connection ultimate capacity. By increasing the percentage of beam steel from 0.0044 to 0.0089 (2-fold increase), the ultimate capacity of connection was increase up to 59%.

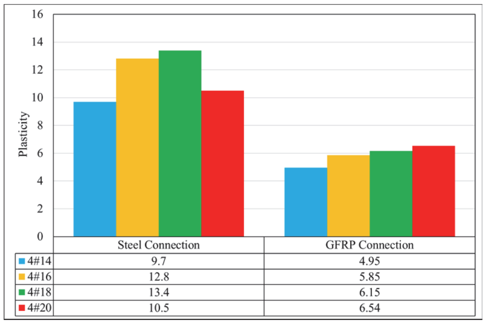


Fig. 11. Comparing the values of plasticity in steel and composite connections

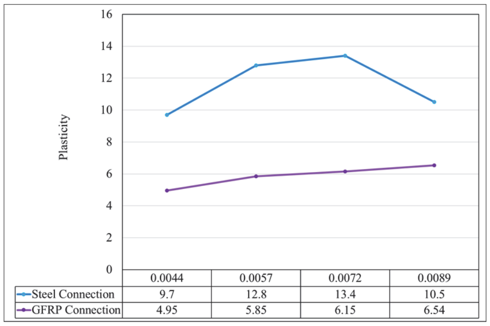


Fig. 12 The trend of plasticity changes in steel and composite connections based on the percentage of section reinforcement

Increasing the percentage of reinforcement in the beam section in the case of using steel rebars leads to increased connection plasticity. However, with the increased percentage of reinforcement and constant beam geometrical dimensions, finally, the plasticity is gradually reduced. It is seen from Fig. 24 that by increasing the percentage of beam steel from 0.0044 to 0.0089 (2-fold increase), the connection plasticity increases up to 8%. The highest possible growth for steel rebars is equal to 38% occurring between the first and the third modes. Increasing the percentage of reinforcement in the beam section in the case of using GFRP rebars leads to increased connection ultimate capacity continuously, but very slowly. Also, increasing the percentage of beam arming from 0.0044 to 0.0089 (2-fold increase), can increase the ultimate capacity of connection up to 32 of 32%.

5. Conclusion

This study has investigated the behavior of reinforced concrete beam-column connection model for two models with steel and GFRP rebars. The parameters included the ultimate strength of the connection, the energy absorption and plasticity. The major findings and results are:

1. Based on the results of ultimate strength in two steel and GFRP connections, it can be seen that replacing steel reinforcement with GFRP reinforcement leads to connection ultimate strength reduction. The observed reduction is obtained equal to 55%.

2. Comparing the time history results of the total energy in two steel and GFRP rebars, it can be seen that the total energy change in GFRP connection is more uniform than the connections with steel reinforcements. Since the steel has a plastic behavior, by entering a non-linear phase, a sudden increase in the total energy is triggered. Comparing the amount of energy absorption in two connections with steel and GFRP reinforcements, it is concluded that the section with steel reinforcement has displayed a higher plasticity. Plasticity reduction in the case of using GFRP rebars is equal to 37%.

3. According to the comparison of plasticity in two steel and GFRP connections, using GFRP reinforcements leads to a decrease in connection plasticity. This reduction is equal to 54%.

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