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**Document Version**
Accepted author manuscript

Link to publication record in Manchester Research Explorer

**Citation for published version (APA):**
Kadhim, M., Wu, Z.-J., & Cunningham, L. (2017). Effects of loading rate on the behaviour of CFRP strengthened steel members. In *Proceedings of the 4th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures: SMAR 2017* (pp. 1-8). Article 278.

**Published in:**
Proceedings of the 4th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

# Effects of loading rate on the behaviour of CFRP strengthened steel members

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ABSTRACT: Over the past three decades, fibre reinforced polymer (FRP) composites have steadily gained popularity in civil engineering applications due to their unique advantages. As a result of the considerable amount of research conducted on the behaviour of CFRP strengthened steelwork under static and fatigue loads, rehabilitation of steelwork using CFRP has increasingly been adopted in field applications. However, up to now, much uncertainty still exists on the dynamic performance and in particular the effects of loading rate on the behaviour of such members.

This paper is aimed at investigating the main differences between the responses of CFRP strengthened steel columns subject to various different loading rates. The basis of this study is an experimental program comprising a series of square hollow section (SHS) columns tested under two loading rates: quasi-static (0.05 mm/sec) and impact (4.43 mm/sec). CFRP was wrapped around the steel section in three different configurations including fibres oriented in the longitudinal direction, transverse direction and in both directions. The effect of co-existing axial compression applied prior and during the application of the transverse impact (or static) load was also examined. The axial load was introduced in the experimental program to simulate the normal service load that exists on columns in multi-storey frame buildings. Generally, it was found that the effectiveness of CFRP strengthening was increased at higher loading rates to different degrees depending on the CFRP configuration.

## 1 INTRODUCTION

Carbon fibre reinforced polymer (CFRP) has been known as having substantial potential for strengthening steel structures (Zhao and Zhang, 2007). Over recent years, it has increasingly been used in rehabilitation of infrastructure as an alternative strengthening technique to the traditional methods. During their service life, building and civil engineering infrastructure may suffer from different kinds of accidental actions which generate some form of impact e.g. vehicular collisions, dropped heavy objects, debris from extreme weather conditions or explosions etc. CFRP has the potential to improve the performance of existing steel structures in these circumstances. Therefore, it is useful to have a comprehensive understanding of the behaviour of CFRP strengthened members under various loading rates.

The response of CFRP strengthened steel columns and beams has widely been investigated under static load. For example, Shaat and Fam (2009) found that the increase in the ultimate load of CFRP strengthened slender SHS steel columns ranged from 6 to 71% compared to the unstrengthened column, depending on the slenderness ratio of steel columns. Similarly, it was found that the ultimate load of CFRP strengthened lipped channel steel columns increased about 15 and 20% compared to the corresponding unstrengthened columns for short and long columns respectively (Silvestre et al., 2008). However, the behaviour of CFRP strengthened steel columns under impact load was lightly investigated. In one of these few studies, Alam and Fawzia (2015) numerically investigated the response of axially compressed CFRP strengthened columns under transverse impact. Another study conducted by Kadhim et al. (2016) investigated the numerical response of a CFRP strengthened steel column under impact load. Both studies showed that this strengthening technique could effectively reduce the transverse displacement of columns for about 60% and 40% for the former and later studies respectively. The main difference between these studies was the omission of the effects of the partial bond between CFRP and steel section by the former study. A further numerical study was carried out by Kadhim et al. (2017) in which the strengthening of I'section steel beams was investigated using various length and thickness of CFRP laminate. It was found that the CFRP can enhance the response of steel beams by reducing the deflection about 13% compared to the corresponding unstrengthened beam. In addition, the dynamic properties of CFRP-steel joints has also been investigated in a number of studies such as (Al-Mosawe et al., 2016; Al-Zubaidy et al., 2012). According to authors' knowledge, no experimental work on the behaviour of CFRP strengthened steelwork under impact load has either been previously conducted or made readily available.

The main aim of this study is to compare the effectiveness of the CFRP in different loading rates. Generally, it is well known that when the loading rate is increased the plastic flow stress of a specific steel member is also increased because of the strain rate effect. However, the increment in the member's strength is usually dependent on the strain rate sensitivity of the member's material. The comparison between the static and impact results was undertaken for eight samples comprising four under static loading and four under impact loading.

## 2 EXPERIMENTAL SETUP

The experimental programme comprised testing eight samples under various loading rates. Square hollow sections (SHS) with dimension 40 mm × 40 mm × 3 mm of steel grade S355 were used to make 0.85 m long samples. Two end plates were welded to each end to allow attachment to the testing rig. CFRP was bonded to four samples while the rest of samples were tested without strengthening. Two of 0.6 mm thickness CFRP layers were wrapped around the steel section to provide 1.2 mm thickness CFRP layer. Two CFRP configurations were examined comprising CFRP being laid only longitudinally or longitudinally and transversely. CFRP coupon specimens were prepared from unidirectional CFRP commercially named Toho Tenax STS40 and tested according to ASTM3039-00 (ASTM, 2000) to investigate the tensile properties. The measured tensile strength, ultimate strain and elastic modulus were 1397.8 MPa, 0.014 and 105.3 GPa. Adhesive material commercially known as Araldite 420 was used to bond CFRP fabric plies to steel surfaces (more information about this kind of adhesive material can be found in Huntsman (2009)). The length of CFRP and thickness were maintained constant at 0.8 m and 1.2 mm respectively. Four samples were tested under quasi-static loading rate (0.05 mm/sec) and the others were tested under low-velocity impact rate (4.43 mm/sec). The effect of preloading level (applied load/ ultimate load) was also investigated in this experiment as listed in Table 1. The following name system is employed to describe each sample: the first letter (C) stands for the column, the second letter (L or LT) denotes that the sample was strengthened with fibres oriented in the longitudinal and both longitudinal and transverse directions respectively, and the last numeric value 0 and 50 denotes the preloading level (percentage) which is equal to applied load divided by the ultimate design load for the column. Also note that the letter "S" refers to static loading rates.

In order to apply the pre-compression load prior and during the test, a special test rig was manufactured. A disc spring pile was used to apply the pre-compression load on the samples as shown in Figure 1. A 650kN capacity Kistler load cell was positioned in the striker system under pre-compression to reduce the effect of vibration on the load cell. The test rig can provide fixed ends (with allowing axial movement in the axial direction at one end) boundary conditions. In both of the static and impact tests, the load was applied to the striking system (see Figure 1) which then transferred to the sample by an indenter. The indenter was made from high-strength steel (EN24). The head of the indenter was carefully rounded with a 2 mm radius to avoid local failure in the specimens. Six strain gauges were mounted on each sample as shown in

Figure 2 to measure the strain profile during the test. All strain gauges were attached in the longitudinal direction apart from strain gauge G1 which was mounted in the transverse direction in the side of the samples under the indenter in order to measure the local strain occurring in this direction and thus indicate the effectiveness of the CFRP (in the transverse direction) in controlling local deformations. The impact load was applied using a 91 kg impactor dropped from 1 m height to provide 4.43 m/sec velocity using a hammer machine which has a 150 kg mass capacity at a 5 m maximum drop height. It should be mentioned that the overall recorded time was 0.05257 sec in the impact tests with one reading taken every 0.000001 sec. The static tests were performed by operating the test rig on an RDP GROUP 200 kN capacity universal test machine, with crosshead speed of 3 mm/min.

Table 1. Sample identification

| Preloading level (%) | CFRP configuration | Preloading level (%) | Loading rate (m/sec) |
|---|---|---|---|
| C0 | - | 0 | 4.43 |
| SC0 | - | 0 | 0.05 |
| C50 | - | 50 | 4.43 |
| SC50 | - | 50 | 0.05 |
| CL50 | Longitudinal | 50 | 4.43 |
| SCL50 | Longitudinal | 50 | 0.05 |
| CLT50 | Longitudinal+ transverse | 50 | 4.43 |
| SCLT50 | Longitudinal+ transverse | 50 | 0.05 |

## 3 RESULTS

The impact test was conducted under constant impact energy which generated by a 91 kg mass dropped with 4.43 m/sec velocity as previously mentioned in Section 2, while in the static test the samples were loaded up to their ultimate load. Figure 3 illustrates that the initial peak force did not have a clear trend due to applying the CFRP in the outer surface of the samples, which dampened the contact interaction and reduced the frequencies contributing in the reduction of the initial peak force (Shakir et al., 2016). The same reason may also cause a delay in the time of the initial peak force due to the non-uniform outer surface (see Figure 3). After this peak force the vibration stage started, this may be influenced by the severe vibrations of both the sample and indenter at the first contact. These vibrations caused rapid changes in the contact force which appeared on the force-displacement plot as spikes of smaller amplitude than the initial peak. Subsequently, the sample and impactor move together and remain in contact. In this stage, the impact force is nearly constant (so-called plateau stage). During this stage, most of impact energy is dissipated due to the relative long duration compared to the other stages (Kadhim et al., 2017). When the sample reaches the maximum transverse displacement, the sample and impactor rebound which so-called unloading stage. However, the comparison between the plateau values of the unstrengthened samples tested under 0 and 50% preloading levels demonstrated that the plateau value reduced when applying axial force on the sample. Regarding the strengthened samples, it can be seen from Figure 3 that the samples strengthened with fibres oriented in both directions had higher plateau values compared to other strengthened samples. This reflects the ability of this configuration to control the local and global buckling.

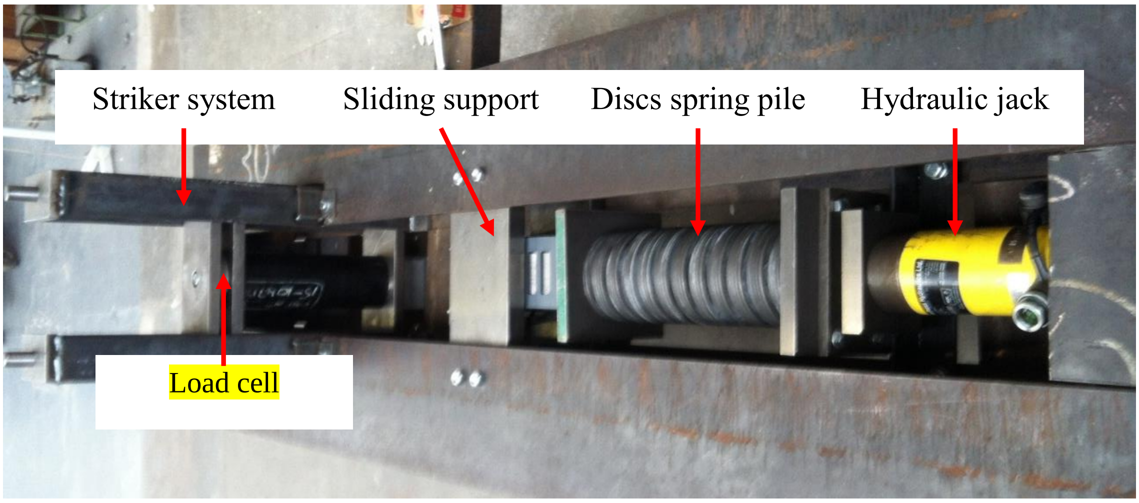

Figure 1. Layout of the test rig.

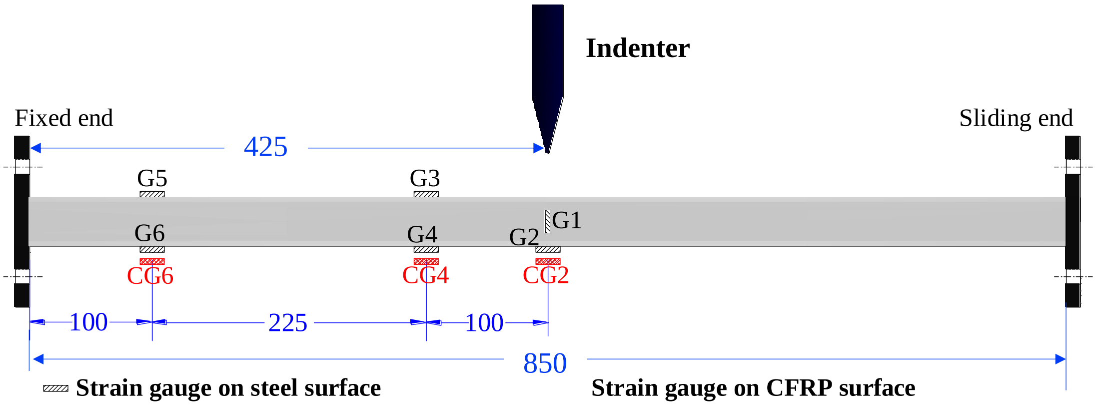

Figure 2. Strain gauge positions.

Concerning the samples tested under quasi-static loading, Figure 4 shows the load-transverse displacement up to their ultimate load. Similar to the trend discussed in the previous paragraph, the unstrengthened sample tested without applying pre-compression force achieved an ultimate load more than the corresponding value of the sample tested with a 50% preloading level. In addition, the increment of the load-carrying capacity of specimen SCLT50 is about 26% compared to the unstrengthened sample (SC50), which is higher than the rest of the strengthened samples.

For both loading rates, no debonding between CFRP and steel members occurred in the tested samples, however, for the quasi-static loading rate steel yielding was the unique failure mode for all tested samples. In the case of impact loading rate, no global failure occurred in the tested samples and the samples were still able to carry more load. It should be mentioned here that in all tested samples some local damage occurred in the impact region under the indenter (see Figure 2).

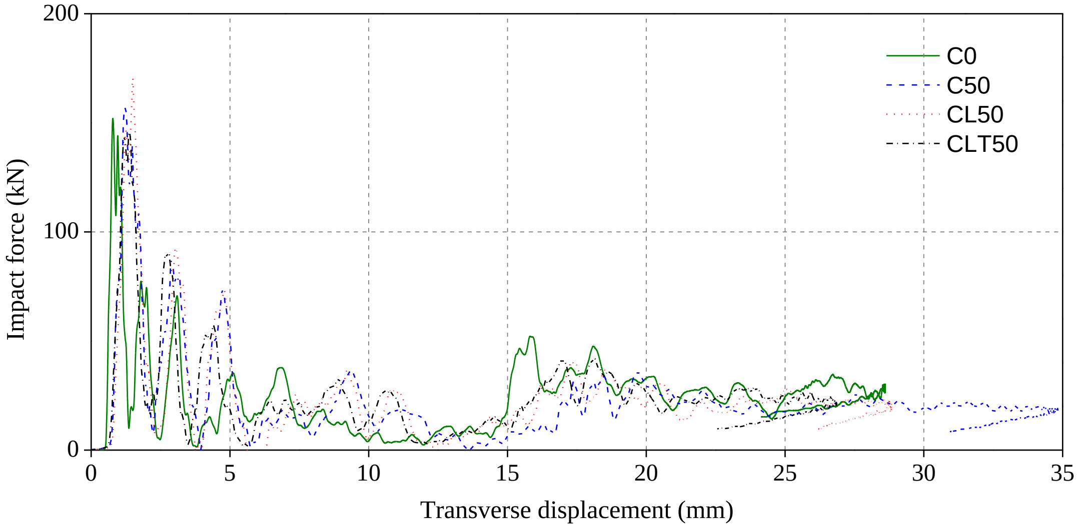

Figure 3. Impact force-transverse displacement for samples tested under impact load at mid-span.

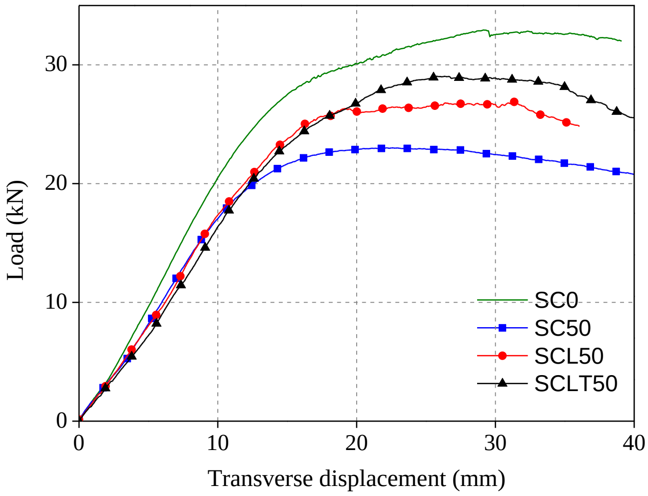

Figure 4. Load-transverse displacement for samples tested under static load at mid-span.

## 4 COMPARISON BETWEEN STATIC AND IMPACT RESULTS

The general trend of both loading rates is usually similar. For example, it was found the columns strengthened with fibres oriented in both directions had the maximum load-carrying capacity (or plateau force for the impact tests) and the minimum transverse displacement compared to the other corresponding columns. However, there were some differences regarding the amount of the applied work on both loading rates in addition to the strain rate effect. In other words, in the static tests, the samples were loaded up to their ultimate load, while in the impact tests constant impact energy was applied to all samples. For example, the internal energies dissipated by samples SC50 and C50, which is represented by the area under force-transverse displacement curve, were 960 and 783 J respectively. Thus, the comparison between the static and impact tests should be undertaken based on a datum. Table 2. presents the total energy absorbed by the samples up to 27 mm mid-span transverse displacement. The limit of 27 mm was chosen because the maximum transverse displacement that occurred for sample CLT50 was 27 mm. Even this comparison might not be very fair because these samples (tested under impact load) reached the 27 mm transverse displacement at different times, which means that they have different strain rates when the comparison is made. However, even with these differences it might be worthwhile to have some basic comparisons between these sets of tests.

Table 2. reveals that the energy dissipated by the steel members tested under impact loading was greater than the corresponding values gained from the static test, which was clearly caused by the strengthening and strain rate effects. This trend seems identical for all compared samples. However, the difference between the dissipated energies (impact and static) for the samples tested without pre-compressive load (C0 and SC0) was less than the associated values for the 50% pre-compressed columns (C50 and SC50). This might relate to the fact that the average strain rate was greater for the samples tested under 50% preloading compared to those without. It should be mentioned that the strain rate has a significant effect on both the behaviour of steel and the specific type of adhesive material used (Araldite 420) as previously reported by other researchers such as (Jones, 1997) and (Al-Zubaidy et al., 2013). However at present, for CFRP itself, there is no consensus on whether the strain rate has a noticeable influence or not. Some researchers have suggested that the effect of strain rate for unidirectional CFRP could be neglected (Harding and Welsh, 1983; Hallett and Ruiz, 1997), while others have argued for the opposite (Al-Zubaidy et al., 2013).

Table 2. Comparison between the internal energies for the static and impact tests

| Preloading level (%) | CFRP configuration | Transverse displacement (mm) | Internal energy (J) | | |
|---|---|---|---|---|---|
| | | | Static | Impact | Difference (impact - static) |
| 0 | - | 27 | 585.5 | 666.4 | 80.9 |
| 50 | - | 27 | 455.5 | 610.7 | 155.2 |
| 50 | Longitudinal | 27 | 489.6 | 655.8 | 166.2 |
| 50 | Both | 27 | 501.5 | 673.6 | 172.1 |

Similarly, the variation between the energy absorbed in the impact and static tests for the samples strengthened in both directions was also greater than the corresponding values for those unstrengthened samples and those strengthened with fibres oriented in the longitudinal direction. It might be possible to conclude here that the CFRP effectiveness increased with a higher loading rate. It is expected that this was caused partly by the strain rate sensitivity of the adhesive and CFRP material, even if this reason might have made only a small contribution. It can be seen from Figure 5 showing the transverse displacement for samples C50 and SC50 against the strain gauge G1 reading that for the same transverse displacement the strain gained from the impact test was greater than the corresponding value for the static test. Consequently, the CFRP provided an extra resistance to the local deformation, which helped to increase the effectiveness of the CFRP.

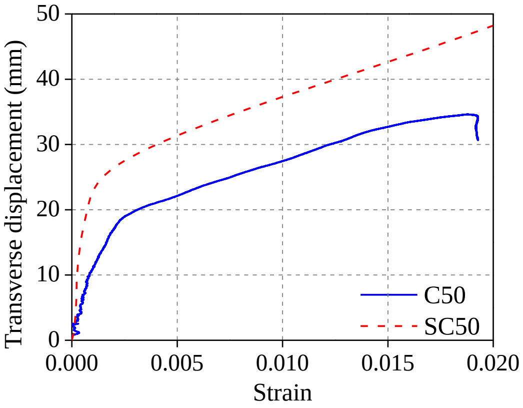

Figure 5: Transverse displacement against strain gauge G1 readings for samples C50 and SC50.

Another example of the comparison between the impact and static loading results was the strain value for various samples listed in Table 3. The strain value in this table represents the strain values from strain gauge G1. The comparison was made for a fixed internal energy value which is equal to 675 J. It can be concluded from this table that the reduction in the strain value was more pronounced in the case of the impact loading rate. Similarly, another comparison can be made for the transverse displacement of the columns, as summarised in Table 4. A similar observation can be found from this table when the reduction in the maximum transverse displacement for the samples strengthened in both directions compared to the unstrengthened columns was 10 and 13% for the static and impact tests respectively.

Table 3. Comparison between the static and impact results with regard to the strain value in the transverse direction at the samples' mid-span

| Loading case | Internal energy (J) | Strain | | Strain reduction (%) |
|---|---|---|---|---|
| | | Unstrengthened | Strengthened in both directions | |
| Static | 675 | 0.0181 | 0.0144 | 20 |
| Impact | 675 | 0.0127 | 0.0095 | 25 |

Table 4. Comparison between the static and impact results with regard to the maximum transverse displacement values

| Loading case | Internal energy (J) | Maximum transverse displacement (mm) | | Transverse displacement reduction (%) |
|---|---|---|---|---|
| | | Unstrengthened | Strengthened in both directions | |
| Static | 675 | 37 | 33 | 10 |
| Impact | 675 | 31 | 27 | 13 |

## 5 CONCLUSION

It can be concluded from the results discussed in this paper that the effectiveness of the CFRP in strengthening steel columns was increased with a high loading rate. However, this increase in the strengthening effectiveness was relatively small because the impact test was undertaken with a low velocity. In general, the CFRP strengthening with fibres oriented in the longitudinal and transverse directions had higher effectiveness than the fibres oriented only in the longitudinal direction even when the same volume of CFRP was used in both configurations. The reason for this is related to the fact that the CFRP with fibres oriented in both directions has an ability to control both global and local buckling of the steel section examined.

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