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Influence of dynamic loading induced by free fall ball on high-performance concrete slabs with different steel fiber contents

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Abstract. One way to provide safe buildings and to protect tenants from the terrorist attacks that have been increasing in the world is to study the behavior of buildings members after being exposed to dynamic loads. Buildings behaviour after being exposed to attacks inspired researchers all around the world to investigate the effect of impact loads on buildings members like slabs and to deeply study the properties of High Performance Concrete. HPC is well-known in its high performance and resistance to dynamic loads when it is compared with normal weight concrete. Therefore, the aim of this paper is finding out the impact of dynamic loads on RPC slabs' flexural capacity, serviceability loads, and failure type. For that purpose and to get answers for these questions, three concrete slabs with 0.5, 1, and 2% steel fiber contents were experimentally tested. The tests results showed that the content of steel fiber plays the key role in specifying the static capacity of concrete slabs after being dynamically loaded, and increasing the content of steel fiber led to improving the static loading capacity, decreased the cracks numbers and widths at the same time, and provided a safer environment for the buildings residents.

Keywords: impact load; flexural capacity; steel fiber; serviceability load; failure pattern

1. Introduction

High-performance concrete can be categorized from other types of concretes by its distinctive properties and constructability. HPC is produced from normal weight concrete with adding other ingredients that make the speciality to it and let it the only suitable for unique engineering requirements (Chen *et al*. 2016, Vinayagam 2012). It can be made from using the same ingredients of conventional concrete with changing the material proportions. Also, it can be produced by altering the way of mixing the ingredients, replacing the way of placing, and modifying the way of curing that are usually followed with the conventional once. In addition, HPC can be developed from adding other ingredients to the conventional concrete, such as flyash, steel fiber, calcined clay, etc.

HPC possesses many properties that make it attractive to be used instead of conventional concrete in many applications. Firstly, the strength of HPC is higher than that of traditional ones, the strength of conventional concrete is less than 50 MPa while the strength of HPC is about 50

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MPa (Al-Jubory 2013). The other properties include high durability, high splitting tensile strength, and high flexural strength comparing with conventional concrete (Wu *et al.* 2016, Singh and Ritu 2016). These properties seem appealing to be used in a number of applications, including bridges, tunnels, tall building, etc. The aforementioned properties make HPC the most convenient type of concrete to be used in buildings that may be exposed to dynamic loads.

Researchers classified dynamic loads into two groups based on how they are generated or created: nature dynamic loads and man-made dynamic loads (Patel *et al.* 2017, Koccaz *et al.* 2008). Earthquakes and winds are examples of natural dynamic loads which are generated from natural sources and apply dynamic loads on buildings. On other hand, vehicle bombs, explosions, etc. are produced from human-made actions. The causes and consequences of dynamic loads and their effect on concrete behavior and properties have drawn the attention of researchers and industries.

The authors of this paper have performed an experimental work to deeply investigate that how much the static loading capacity of HPC slabs would be affected after being exposed to impact loading. This gives a good indication to the structurers to design safer buildings. In this study, three concrete slabs having dimensions of (800X800X40) mm subjected to dynamic load by the author AL Zahid (2016) were statically loaded one more time. Steel fibers have been added to three slabs in proportion of 0.5%, 1%, and 2% as a ratio of cement content. So, the steel fiber content is the changeable parameter in this study to get a better idea about the importance of steel fiber in reducing the influence of impact loading on the HPC slabs.

2. Material and method

In this section, the used materials in manufacturing the three HPC slabs, the material tests, the slabs dynamic tests, the slabs static tests, and the test results are given in details.

2.1 Material properties of HPC slabs

HPC of the slabs was made by adding steel fiber into the normal concrete ingredients. A brief description of every ingredient is included here.

- Cement: an Ordinary Portland cement, produced locally in Najaf city, Iraq, was used in making the slabs.
- Fine Aggregate: Fine aggregate with particles sizes located within the range (600-150) μm was utilized. The large sizes of aggregate were isolated to get dense concrete.
- Silica Fume: Pozzolanic material was added to cohere the concrete ingredients and to work as a filling material (Rasol 2015).
- Steel Fiber: it is included in the mix to improve concrete ductility (Baarimah and Mohsin 2017) and to enhance the other concrete properties. The used SF is made in China with the following properties: 13 mm average length, 0.2 mm diameter, and with a tensile strength of more than 2300 Mpa.
- Glenium: Glenium 54 is the superplasticizer that was used to produce HPC by reducing water and by improving the workability of the produced concrete (Maroliya and Modhera 2010).

2.2 Impact testing machine

AL Zahid (2016) manufactured the apparatus shown in Fig. 1 to measure the dynamic capacity of the HP concrete slabs.

In addition to using I and rectangular sections in making the apparatus as shown in Fig. 1, other parts were included to enable the apparatus from doing its job, such as a steel ball, an electronic accelerometer sensor, an electronic infrared sensor, and an electronic ultrasonic sensor.

A steel ball of (5) Kg acts as a free falling mass to cause an impact loading on the slabs. Next, the electronic accelerometer sensor was used to find the acceleration of the steel ball by recording the impact force generated by the ball with time. While the electronic infrared sensor was required to measure the displacement of the slabs with time. Finally, the electronic ultrasonic sensor was necessary to record the lateral displacement of the slabs with time.

Fig. 1 Impact testing machine with sensors

2.3 Method of performing the impact loading test

After placing the HPC slabs on the apparatus by the researcher AL Zahid (2016), the steel ball was freely dropped on the top center of the top face of the slabs from a height of 120 cm. The sensors were placed at the following positions: the accelerometer sensor was fixed on the ball to provide the author with the impact force and time data, the infrared sensor was installed at the bottom center of the bottom face of the slabs to record the displacement and time data, and the ultrasonic sensor was put in a way where the lateral displacement could be recorded.

2.4 Method of testing the static loading

Many research articles found in literature have studied the properties and behavior of both of HPC and conventional concrete. For example, Aravind, Senthil, and Manikandan (2017) published a paper about the flexural capacity of reinforced high performance Reactive Powder Concrete beam having dimensions of (1.5X1.5X0.18) m. Jia *et al.* (2014) investigated the HPC behaviour under the effect of impact loads by applying blast loads on two ways reinforced concrete slabs.

However, these papers did not give enough information about how HPC or conventional concrete would behave after being subjected to dynamical load. This motives the authors of this work to deeply investigate the behavior of HPC slabs after being subjected to impact loads. For this purpose, the slabs were statically loaded later than dynamically loaded.

In static loading case, each slab was placed on the flexural strength testing machine. The type of supports was simple supports that were prepared by welding a roller on the frame of the device as illustrated in Fig. 2.

In case to apply a static loading in both directions of each slab, a solid square cube was used. Moreover, a dial gage was set at the center of the bottom face of the slabs to record the caused deflection by the applied static load till failure.

Fig. 2 Flextural strength testing machine

3. Results and discussions

The results of the three tests: compression test, dynamic test, and static test are given in this section, and the results' discussion is included as well.

3.1 Compression test results

For each slab, three cubes were sampled and tested by AL Zahid (2016). The results of the test are summarized in Table 1. The slab with 0.5% steel fiber is named as T4F, the HPC slab with 1% steel fiber is named as T4SF1, and T4SF2 refers to the HPC slab with 2% steel fiber.

3.2 Impact loading test results

The maximum impact loads and the corresponding deflection are included in Table 2 (AL Zahid 2016).

From Table 2 the slab with the highest steel fiber (T4SF2) provided the highest impact loading capacity of (6.93 KN) and the least deflection of (2.277 mm). In addition, the same slab had the narrowest crack width; the crack widths caused by the dynamic loading are comprised in Table 3.

Moreover, the slabs' cracks numbers, widths, and lengths are compared as well. Fig. 3 shows the cracks' patterns of the slab T4F, where it had the highest number of cracks and the longest cracks than the other two slabs. Besides, the cracks were extended throughout the four quarters of the bottom face of the slab.

Table 1 Average compressive strength test of three cubes

Slab	Compression strength, MPa	Age (Day)
T4F	88.42	51
T4SF1	84.46	56
T4SF2	104.09	57

Table 2 Impact test results

Slab	Impact load (KN)	Deflection (mm)
T4F	5.57	5.09
T4SF1	6.48	3.3
T4SF2	6.93	2.28

Table 3 Average crack widths of slabs

Slab	Average crack width (mm)
T4F	0.054
T4SF1	0.029
T4SF2	0.02

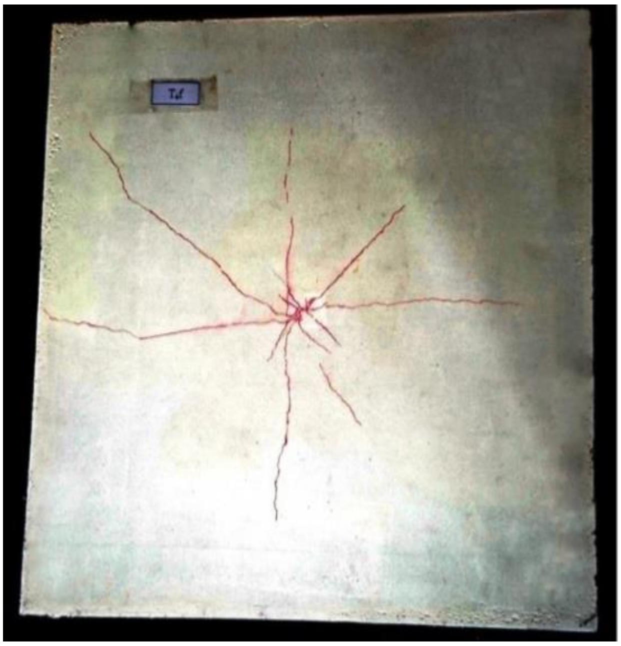

Fig. 3 Crack pattern of the slab T4F

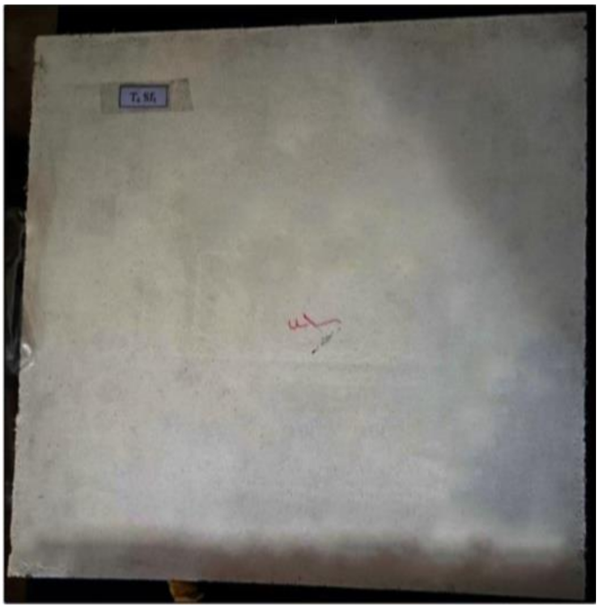

Fig. 4 Crack pattern of the slab T4SF1

The slab T4SF1 had only one crack at the center of the bottom face of the slab as shown in Fig. 4.

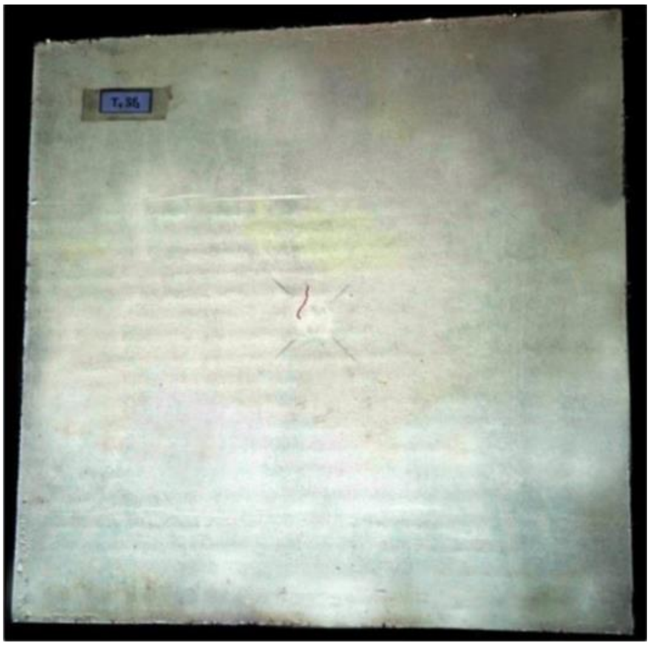

Fig. 5 Crack pattern of the slab T4SF2

The slab T4SF2 had also one crack, but shorter than the crack of the slab T4SF1 at the center of the bottom face of the slab as illustrated in Fig. 5.

3.3 Static loading test results

As mentioned previously, the three slabs that were subjected to impact loading were loaded statically one more time. The static loading with increment of 0.5 KN till failure was applied on each slab. The deflection was recorded for each increment till failure. The maximum static load and deflection corresponding for the maximum load of the slabs are included in Table 4.

The results from Table 4 reveal that the maximum flexural capacity of the slabs increases with increasing the steel fiber content in concrete. Therefore the slab with the highest steel fiber content (T4SF2) withstood the highest load (46.5 KN). Moreover, the load and deflection increments are not linear with steel fiber content increments. Fig. 6 illustrates the development of load- deflection curves of the HPC slabs.

Table 4 Flexural test results

Slab	Impact load (KN)	Deflection (mm)
T4F	16	4.13
T4SF1	38.5	11.37
T4SF2	46.5	13.48

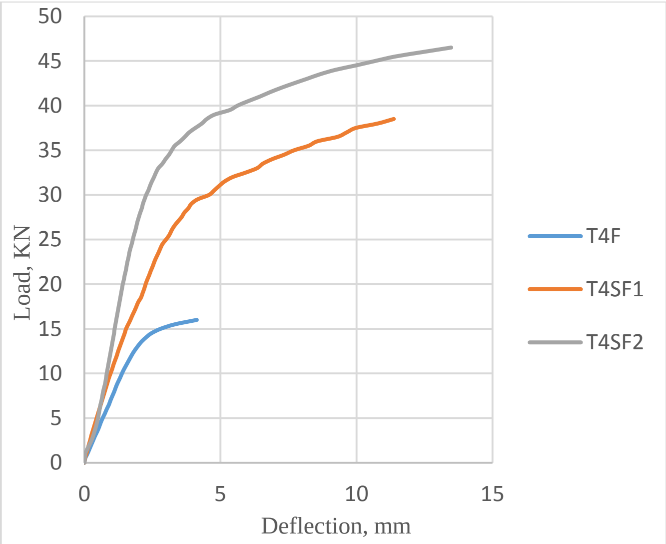

Fig. 6 Load-deflection curves of the slabs

As shown in the preceding sections, the created cracks by the static loading are remarked and compared. Also, the comparison included the average cracks widths, cracks numbers, and cracks directions. To distinguish between dynamic and static cracks, the dynamic cracks were signalized by utilizing a red marker, while the static cracks were marked by utilizing a blue marker.

The slab T4F after being statically loaded, the cracks caused by the impact loading were more widened and lengthened. The average crack width was raised from 0.0537 mm to 0.38 mm, and the cracks were more extended into the edges of the slab. Next, new cracks showed up and started from the center toward the edges of the slab. Fig. 7 shows the crack patterns of the slab later than statically loaded.

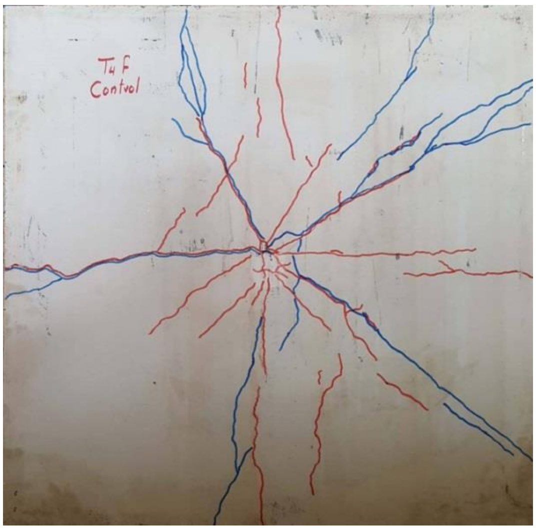

Fig. 7 Dynamic-static crack pattern of the slab T4F

Fig. 8 Dynamic-static crack pattern of the slab T4SF1

Fig. 8 illustrates the cracks patterns of the slab T4SF1 after loading it statically. As shown from the figure, four main new cracks appeared spreading out through the four quarters of the bottom face of the slab, beginning from the center of the slab toward the edges. The average crack width is 1.0675 mm.

While the slab T4SF2 had three main new cracks with a circular fourth crack at the bottom face of the slab as shown in Fig. 9. The circular crack was surrounding or following a path that connects the four corners of the square cube through which the load was transferred from the loading machine to the slab. Next, the other cracks started their paths from the outer edge of the circular crack. The average crack width is 1.1925 mm.

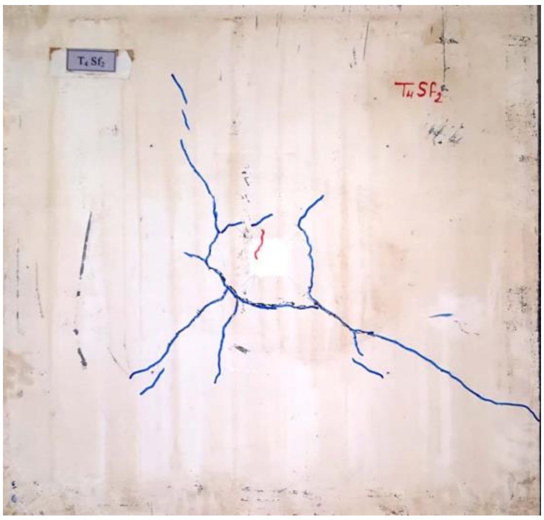

Fig. 9 Dynamic-static crack pattern of the slab T4SF2

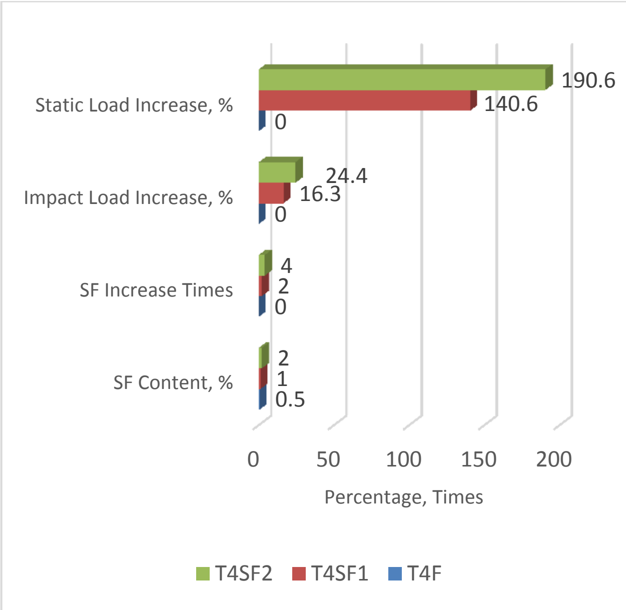

Fig. 10 Influence of steel fiber content increase rate on the dynamic and static loading capacity of HP concrete slabs

3.4 Results discussion

The results of dynamic and static loading tests of the three HPC slabs of 40 mm thickness and with 0.5%, 1%, and 2% steel fiber content are discussed in this section. The discussion is written depending on the research outputs and observations.

It is obvious from the results mentioned before that steel fiber content in concrete plays the main role in specifying the maximum resisting capacity for impact loading, maximum flexural capacity, cracks widths, cracks numbers, deflection, and/or type of failure of HP concrete slabs.

Regarding maximum loading capacity, increasing steel fiber content in concrete led to increasing the resisting capacity of the HP concrete slabs for both of dynamic and static loading. For instance, increasing the steel fiber content in concrete by two times raised the slabs resistance for impact loads by 16.3% and for static loads by 140.6%, while increasing the steel fiber content in concrete by four times led to increasing the slabs resistance for impact loads by 24.4% and for static loads by 190. 6%. Fig. 10 illustrates the effect of raising up the steel fiber content on both of dynamic and static resisting capacity of HP concrete slabs. As it can be noticed from the figure, the slab, T4F, is the one that is taken as control slab, and all increasing and decreasing percentages in this figure and all other following figures are made by comparing the other two slabs with this slab.

Concerning slabs' crack widths, steel fiber content in HPC slabs showed a key role in decreasing crack width when they were subjected to impact loads. The rate of decreasing the crack width was relative to steel fiber content and the maximum resisting capacity that the slab can withstand. For example, increasing steel fiber content by two times increased the loading capacity by 16.3% (as shown in Fig. 10) and decreased cracks width by 46.6%, and increasing steel fiber content by four times increasing the loading capacity by 24.4% (as shown in Fig. 10) and decreased crack width by 62.8%. Fig. 11 shows the influence of steel fiber content on decreasing the slabs' crack width.

Succeeding that the three slabs were loaded statically, and the cracks width increased relatively with increasing the loading capacity of the slabs. When the steel fiber content was increased by two times, the static loading capacity was increased by 140.6% (as shown in Fig. 10), and the crack width was also increased by 180.9%. while increasing steel fiber content by four times led to increasing the static loading capacity by 190.6% (as shown in Fig. 10), and the crack width was also increased by 213.8%. Fig. 12 illustrates the relation between the steel fiber content and cracks width of the HP concrete slabs. As it is clear from Figure 12, the increase rate of crack width is higher in the second case; of course that is because concrete ductility is higher.

Respecting deflection, the higher steel fiber content in concrete, the less deflection was generated in slabs and for both loads: dynamic and static. Increasing steel fiber content by two times decreased deflection of the HPC slabs by 35.1% when dynamically loaded and by 59.1% when statically loaded, while increasing steel fiber content by four times reduced deflection of the slabs by 55.2% when dynamically loaded and by 71.7% when statically loaded. Fig. 13 shows how deflection of HP concrete slabs could decrease by increasing steel fiber content in concrete.

Failure type of slabs depends upon a number of factors, such as type of concrete: normal or high performance, type of loading: impact or static, point of loading, amount of loading, etc.

Fig. 11 The relation between steel fiber content increase times and crack widths of HP slabs

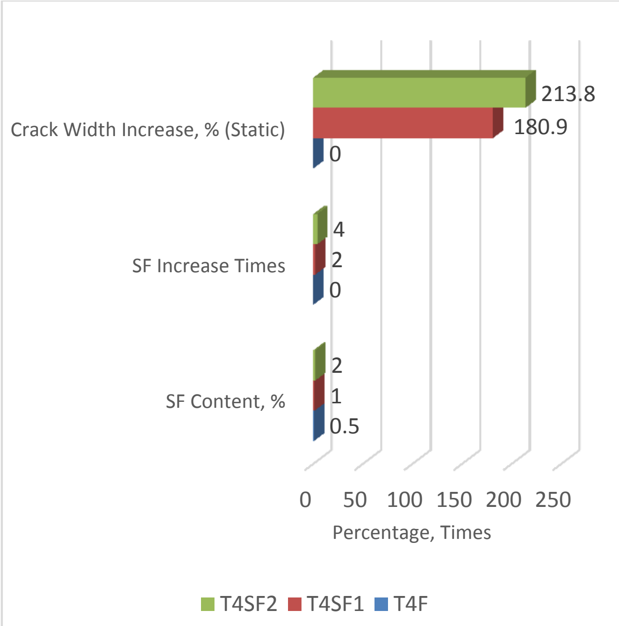

Fig. 12 The relation between steel content increase times and cracks width of HP concrete slabs

For dynamic loading case, Jia, Yu, and Wu (2014) proved that the type of failure relies mainly upon explosives weights and their hitting positions of the slabs whether they would hit slabs at their center or at one of their borders. Besides, they specified that the damage degree of slabs would increase by increasing the explosive amounts and/or by moving the hitting point toward the slabs borders away from their centers, and the failure type would change in order from flexural failure type into flexural shear failure type. As a result, those factors were found are the main factors in specifying the failure type of concrete slabs when they would be statically loaded after that. For this limited study, although the two factors: impact load and hitting position are unchanged factors for all slabs, different failure types were obtained; that is because the difference in steel fiber content in the slabs' concrete. The failure type of the slabs T4F and T4SF1 was found to be flexural failure, while the type of failure of the slab T4SF2 was punching shear.

The final discussion, which is considered the most important one, is about buildings residents´ life. Structurers of buildings, especially buildings that possibly expose to explosions, concern about the sudden collapse of buildings. Therefore, presence of steel fiber in concrete helps in revealing those concerns by slowing down the cracks progression. In fact, one of advantages of using steel fiber is increasing concrete ductility, altering by that the failure mode of concrete slabs from a brittle mode into a more ductile one (Behbahani *et al.* 2011, Dehake and Charkha 2016). Hence, using steel fiber in slabs will provide safer buildings for their occupants. The second advantage of using steel fiber in concrete is there will be more available chance to repair slabs of buildings after being subjected to impact loads, since the generated cracks numbers and cracks widths are not reaching the case as it was observed in the slab T4F where many, big cracks were generated, causing a difficulty for constructers to maintain them.

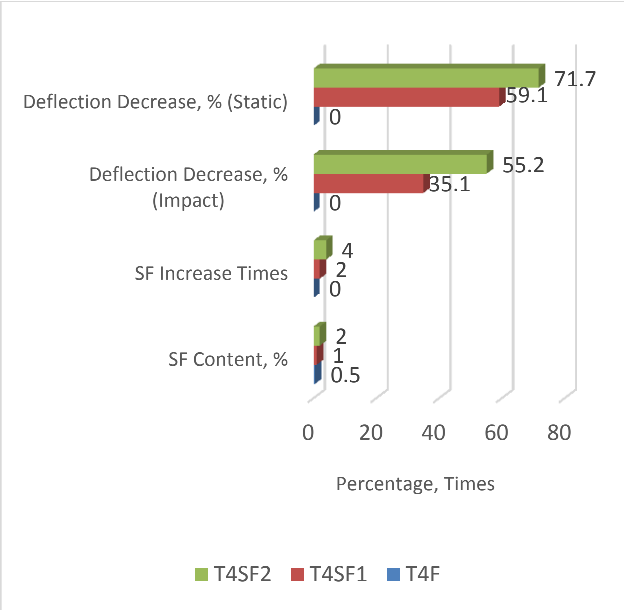

Fig. 13 Effect of steel fiber content increase times on the dynamic and static deflection of HP concrete slabs

4. Conclusions

The necessity that inspired researchers all around the world to deeply study the behaviour of concrete slabs after being exposed to impact loads and to specify the decrease percentage in the flexural capacity of slabs is the raising up rate of subjected buildings to explosions and terrorist attacks. Therefore, three concrete slabs with the same dimensions and thickness, but with various steel fiber content (0.5%, 1%, and 2%) were experimentally tested. The research results showed that the slab with the highest steel fiber content withstood the highest impact load, provided the highest resistance to flexural loads, had the least deflection, had the least cracks numbers, and was the safest slab for buildings residents than the other two slabs.

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