Cracking Behavior of UHPC slabs

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Abstract

The combination of fibers with traditional reinforcement may be a very interesting design solution to achieve more durable and economical structures. In this study, a total of seven slabs; six ultra high performance concrete (UHPC) slabs and one normal strength concrete slab were tested previously by the Author to observe the crack spacing and number of cracks in tension area, crack width and absorbed energy. Four slabs of UHPC with steel fiber of 0.5%, one UHPC slab with 1.1% steel fiber and one slab of UHPC without steel fiber were used in the analysis. For UHPC, the contribution of fibers to cracking in terms of crack width and spacing is significant when the amount of fibers increased. Also, normal strength concrete slabs have longer crack spacing as compared with UHPC members.

سلوك التشققات للسقوف الخرسانية الفائقة الكفاءة

الخلاصة

اضافة الالياف الى الخرسانة المسلحة يعتبر من الحلول التصميمية المهمة لانتاج خرسانة اقتصادية ولها ديمومة عالية. في هذه الدراسة تم الاستعانة بنتائج الفحوصات التي اجريت في السابق بواسطة الباحث لستة سقوف من الخرسانة الفائقة الكفاءة وسقف واحد من الخرسانة العادية لايجاد مسافة بين التشققات, عدد التشققات, عرض التشققات والطاقة الكامنة. اربعة سقوف من الخرسانة الفائقة الكفاءة تحتوي على % 0,5 الياف الحديد وسقف واحد من الخرسانة الفائقة يحتوي على % 1,1 الياف الحديد وسقف واحد من الخرسانة الفائقة لا يحتوي على الياف الحديد. تأثير محتوى الياف الحديد بالنسبة للخرسانة العالية الكفاءة هو كبير ضمن عرض ومسافات التشققات. مسافات التشققات الخرسانية العادية هي اكبر مقارنة بالمسافات للخرسانة الفائقة الكفاءة.

INTRODUCTION

Fiber-reinforced concrete (FRC) is a cement-based composite material reinforced with discrete, usually randomly distributed, fibers. Fibers of various shapes and sizes produced from steel, synthetics and glass. However, for most structural purposes, steel fibers are the most used of all fiber materials, whereas synthetic fibers (e.g polypropylene and nylon) are mainly used to control the early cracking (plastic-shrinkage cracks) in slabs (1). Fiber reinforcement mainly enhances the post-cracking properties of concrete and leads to more ductile material behavior. The increase ductility is due to the ability of the fibers to transfer extent of the crack-width reduction which depends on the

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amount of fibers added as well as their physical properties (e.g. surface roughness and chemical stability) and mechanical properties (e.g. tensile strength) (2).

Typical applications where steel fibers may be used as sole reinforced include slabs on grade and tunnel linings. In other applications the steel fibers are used as a complement to the conventional reinforcement where, in some cases the amount of conventional reinforcement can be reduced. Extensive research has been carried out by technical committees in several countries, such as RIMEM TC 162-TDF (3), and CNR-DT 204/2006 (4), which has resulted in recommendations / guidelines for design of steel fiber reinforced concrete (SFRC). Although the use of SFRC in structural applications is already a common practice within the construction field, generally accepted design methods have not yet been established. Due to this, many engineers are hesitant to use SFRC. If the technique with fiber-reinforced concrete is to be further developed and accepted by practicing engineers, the concrete community should agree about the design methods to use, refine them, and introduce them in codes.

Likewise, the efforts of the researches towards understanding the material and its structural response must also be highlighted. There have been numerous experimental campaigns to study the mechanical properties of FRC: the compressive strength (5), the flexural behavior (6), the pull out, the tensile strength (7), the tension stiffening (7) and the fatigue in compression (8).

The capacity of the structures to bear internal stresses produce by external loads is as important as the capacity of a structure to resist environmental effects; physical or chemical attacks as well as other deteriorating processes, with a minimum of maintenance. Cracks turn concrete structures into permeable elements thus entailing a high risk of corrosion. Cracks not only reduce the quality of concrete and make it aesthetically acceptance, but may also end up rendering the structures unserviceable.

Durability is together with function and aspect considerations, one of the criteria on which the necessity to limit the crack opening is based. The research works dealing with cracking of FRC show that the presence of fibers in concrete helps achieving this goal due to the increase in the crack-bridging capacity.

Research Significant

There are numerous references in the literature to experimental campaigns with FRC elements at the level of sample or specimen. In this study, mixed steel fiber with traditional steel reinforcement are used in constructed the UHPC specimens in order to get a very competitive design solution to obtain more durable and economical structure. So, the main goals of this study are studying and analyzing the effect of following factors: fiber content, compressive strength, reinforcement ratio, slab thickness, and yield stress of tension reinforcement on crack spacing, crack number, crack width and energy absorbed.

Experimental program

The experimental work in this study was conducted previously by the Author in the Structural and Materials Laboratories - Institute of Structural Engineering/ University of Kassel (9). The experimental program can briefly be described as follows:

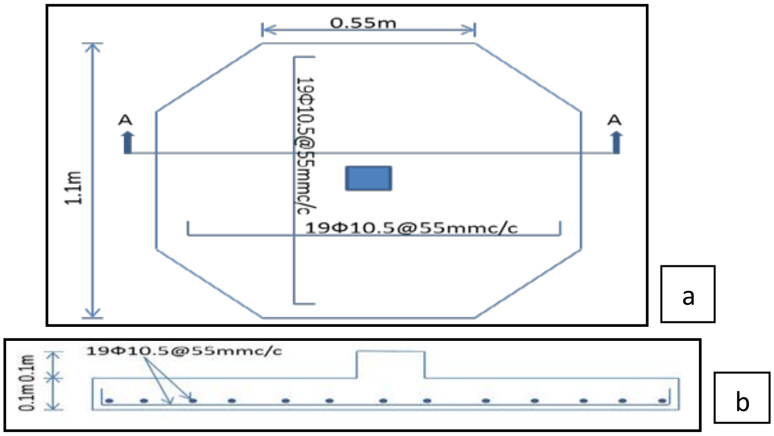
A total of seven slabs were investigated: six UHPC slabs and one normal strength concrete slab. The characteristics of the tested slabs with reinforcement details are summarized in Table 1.

Table (1): Details of tested slabs

Slab	Concrete type	f_c (MPa)	f_{tm} (MPa)	f_{te} (MPa)	h (mm)	fiber content %	E (MPa)	d_{bar} (mm)	ϱ (%)	f_y (MPa)
G1Ufib	UHPC	198.5	4.2	-	100	0	49024	10.5	2	1320
G1Ufib	UHPC	198.9	5.9	3.9	100	0.5	51810	10.5	2	1320
G1Ufib	UHPC	208.2	7.1	7.9	100	1.1	52443	10.5	2	1320
G2Nfc4	NSC	40.3	2.8	-	100	0	27537	10	2	562
G3Uρ1	UHPC	198.9	5.9	3.9	100	0.5	51720	10.5	1	1320
G4Ut55	UHPC	199.2	6.0	3.95	55	0.5	51633	8	2	1570
G5Ufy5	UHPC	198.2	5.8	3.85	100	0.5	51521	10	2	562

In Table 1, the first column represents the code of tested slabs, f_c means compressive strength of concrete, f_{tm} is the matrix tensile strength of concrete, f_{te} is the fiber efficiency of tensile strength of concrete, h is the thickness of tested slabs, d_{bar} is the diameter of reinforcement bars, ρ is the reinforcement ratio, f_y is the yield stress of tension reinforcement.

All tested slabs had an octagonal shape with 550 mm long sides. The stub column has a cross section of 100 x 100 mm and a height of 100 mm. A specimen with these dimensions represents a model scale of about 50% to the negative bending moment region around the interior supporting column of a flat floor slab with 5 m span in both directions. The points of contraflexure are assumed to be 0.211 times the span apart from the supports. By removing the corners of the slab, the final shape of tested slabs will be according to Figure 1. The service gravity load on this slab included 4.6 kN/m^2 self-weight, 1 kN/m^2 additional dead load regarding on floor finishing and partitioning walls, and 3.5 kN/m^2 superimposed live load.



Figure(1): (a) Slab specimen; b) Section A-A in tested slab

The steel fiber type that was used in this study has a length of 20mm, diameter of 0.25 mm, aspect ratio of 80 and the ultimate tensile strength of 2000 MPa.

The M3Q mix proportion applied in Material Engineering department / University of Kassel was used for all UHPC slabs. Table 2 summarize the compositions of M3Q mix design for UHPC slab and also mix design for normal strength concrete.

Table 2: Composition of a) UHPC slab with 0.5% steel fiber; b) UHPC slab with 1.1% steel fiber; and c) NSC slab

a)

Material	Weight [kg]
Water	18.3
portland cement	86.2
Silica fume	18.3
Superplasticizer	3.2
fine quarz	20.9
sand 0.125/0.5	101.9
steel fiber (0.25mm/20mm)	4.1

b)

Material	Weight(kg)
Water	18.19
portland cement	85.75
Silica fume	18.19
Superplasticizer	3.24
fine quarz	20.78
sand 0.125/0.5	101.34
steel fiber (0.25mm/20mm)	9.15

c)

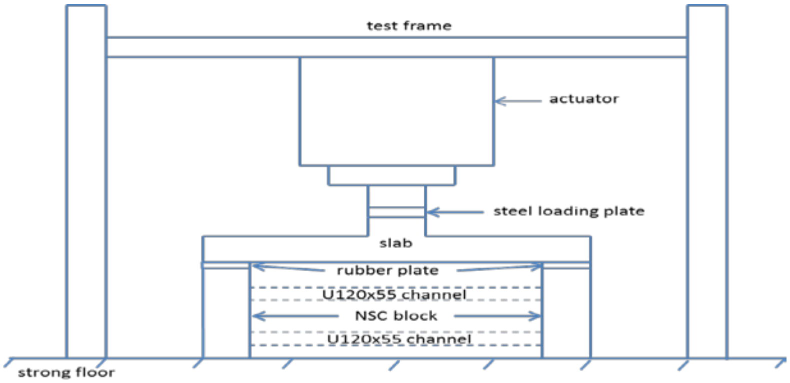
Material	Weight(kg)
Water	20.15
portland cement	32.73
Sand 0/2	76.7
Gravel 2/16	73.53
Water / cement ratio	61.5%

Measurements

The applied vertical load was measured using an accurately calibrated load cell. A camera with references crack width measured was used under the slab to monitor the crack patterns and to measure crack width and spacing.

Testing Procedure

The test setup and slab under test are shown in Figure 2 and 3 respectively, the camera and the references crack width measuring located under the slab to monitor the crack development and crack width. The vertical load was applied to the stub column by displacement control of 0.01mm/sec. In all tests, loading was continued beyond the peak load to obtain the whole crack patterns. As the crack patterns were completed, the load was removed to allow taking more photographs of the final cracks and failure patterns.



Figure(2): Test setup

Figurer(3): Slab under test

Results

The results presented in this paper are structured in three sections depending on the variables analyzed: crack number and spacing in tension area, crack width in tension area and energy absorption. In the analysis of crack width the serviceability limit state and the ultimate limit state is taken into consideration with the purpose of obtaining a global view of the behavior of the elements.

Crack number and spacing

The whole tension area of tested slab between the supports is used in the analysis of crack number and spacing, and the shear cracks due to concentrated load at mid span is excluded in this analysis. The set of diagrams in Figure 4 shows the crack patterns for each tested slab at failure.

UHPC elements with steel fiber tends to present deeper positions of the neutral axis with respect to UHPC without steel fiber, thus smaller crack spacing and larger number of shorter cracks is expected to occur. In this respect, the same phenomenon was observed in this experimental campaign (see Table 3) when comparing the crack spacing between G1Ufib0 and G1Ufib0.5 slabs.

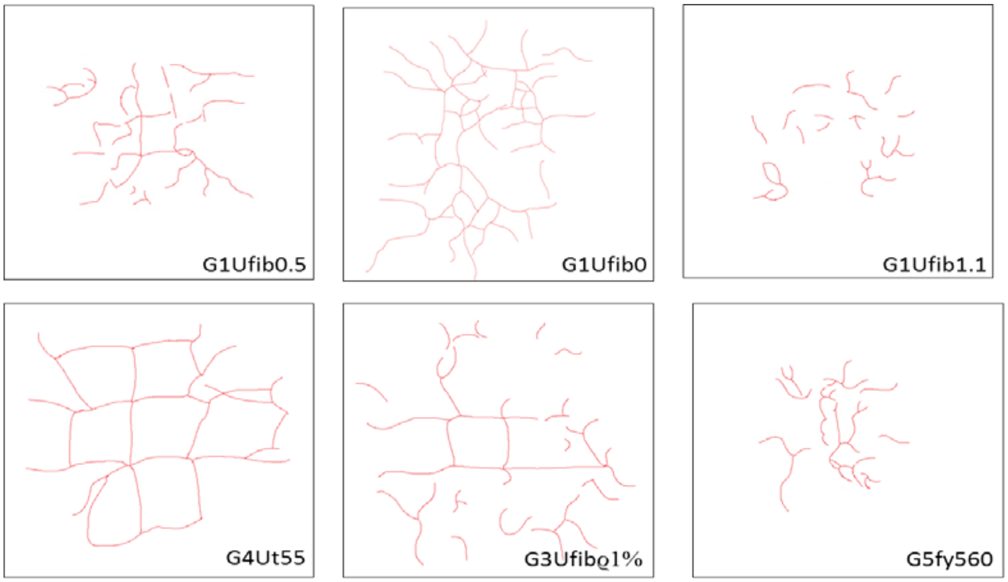


Figure (4): Crack pattern of tested slabs

Table (3): Crack Spacing of all tested slabs

Slab	**Average Crack Spacing (mm)**	**Average number of cracks**	**Crack spacing predictions according to RILEM (mm)**
G1Ufib0	80.5	93	102.5
G1Ufib0.5	99.5	81	64.0
G1Ufib1.1	61.4	69	64.0
G2Nfc40	108.7	80	62.5
G3Uρ1%	54.8	166	96.8
G4Ut55	69.65	85	56.25
G5Ufy560	76.95	80	62.5

The average crack spacing in Table 3 were measured in both direction of slab plane after failure in tension area, from which, when the fiber content increased from 0.5% to 1.1%, the crack spacing increased by 62%, this is expected due to the increase in the arrested area to crack opening. For slab of zero fiber content (G1Ufib0) this slab shows at beginning flexural crack behavior and then the failure transfer to splitting concrete cover mode of failure which make the spacing of cracks bigger as 0.5% fiber content slab.

It is expected, that the UHPC slab with reinforcement ratio of 1% has less spacing than that of 2% reinforcement ratio. The spacing was increased when the slab has small thickness or using normal yielding stress, may be this is because of the effect of early yielding of tension reinforcement which effect on crack spacing.

It is very interested to see that the normal concrete has biggest crack spacing and the ratio is 1.77 and 1.09 times of UHPC with 0.5% and 1.1% fiber content respectively, this is because of aggregate interlock mechanism control the crack spacing in normal concrete and UHPC is cement paste material only the fiber can control the forming of cracks.

RILEM (10), proposed an equation for computing crack spacing for fiber reinforced normal strength concrete, Equation 1.

$$S_{cr} = \zeta\left(50 + 0.25k_1k_2\frac{\phi}{\rho}\right) \qquad \text{.....(1)}$$

S_{cr} is the Crack spacing

ξ is a dimensional coefficient equal to 1.0 when $l_f / d_f < 50$, equal to $\frac{50}{lf-df}$ when $50 \le l_f / d_f \le 100$ and equal to ½ when $l_f / d_f > 100$

d_f is the fiber diameter

l_f is the fiber length

ϕ is the bar diameter used for constructed the specimens

k_1 is 0.8 for high bond bars, 1.6 for smooth bars

k_2 is 0.5 by pure or composite bending when $y \le h$, is 1.0 for tension or When $y > h$

y is the distance of the neutral axis from the extreme edge in compression

h is the section height

ρ is the geometric reinforcement ratio

According to Table 3, there is a big difference between the prediction according to RILEM and the experimental values measured from tests; this is due to aggregate interlock. So, RILEM is applied only for NSC and cannot be applied to UHPC element.

In general terms of Table 3, it can be observed that the addition of fibers to UHPC slabs causes the appearance of a higher number of cracks and consequently smaller spacing. This behavior is mainly due to; the enhancement of the bond between rebar's and concrete due to presence of fibers leading to reduction of the bond transfer length and the post–cracking behavior of the concrete reinforced with fibers.

It is clear that, slab G1Ufib0 (UHPC without steel fiber), and slab G2Nfc40 (NSC) crack spacing is ruled by the transversal reinforcement, due to absence of steel fibers.

Crack Width

The approach almost universally used to explain the basic cracking behavior of normal strength reinforced concrete (NSRC) is to consider the cracking of a concrete prism reinforced with a central bar which is subjected to pure tension. Bending does not influence the phenomena but this is dealt with in the Eurocode by an empirical adjustment of the coefficients.

According to Eurocode (EC2 EN 1992) (11), the design crack width can be determined using the following expression.

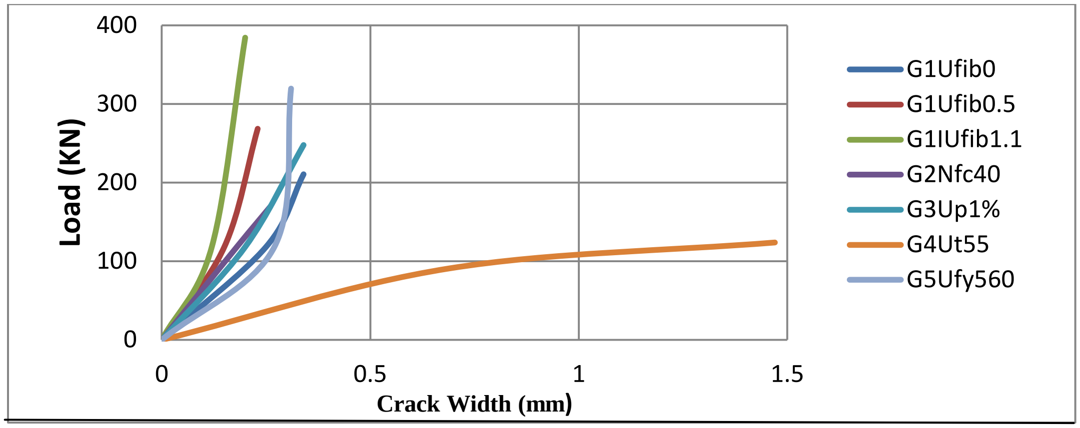
$w_k = S_{cr} (\varepsilon_{sm} - \varepsilon_{cm})$ …..(2)

Where;

w_k is the design crack width; S_{cr} is the maximum crack spacing; ε_{sm} is the mean strain in the reinforcement; ε_{cm} is the mean strain in concrete between cracks.

In this study, the crack width is measured only on the tension side and in service and ultimate load stages using a camera located under tested slabs during testing as previously mentioned. from Figure 5 and Table 4, all the slabs have an increased crack width when transfer from service load stage to ultimate load stage as expected. UHPC slab with 1.1% fiber content shows less cracks width at both stages, this is due to increase the arrested area of crack width. while, in normal strength concrete slab (G2Nfc40) the crack width in both load stages was more than that of UHPC slab of 1.1% fiber content by 33% and 23% respectively; this is due to absence of steel fiber which is active by forming arrested area around the crack and bridging effect. UHPC slab with 55mm thickness shows largest crack width at service load stage and increasing significantly in the ultimate load stage.

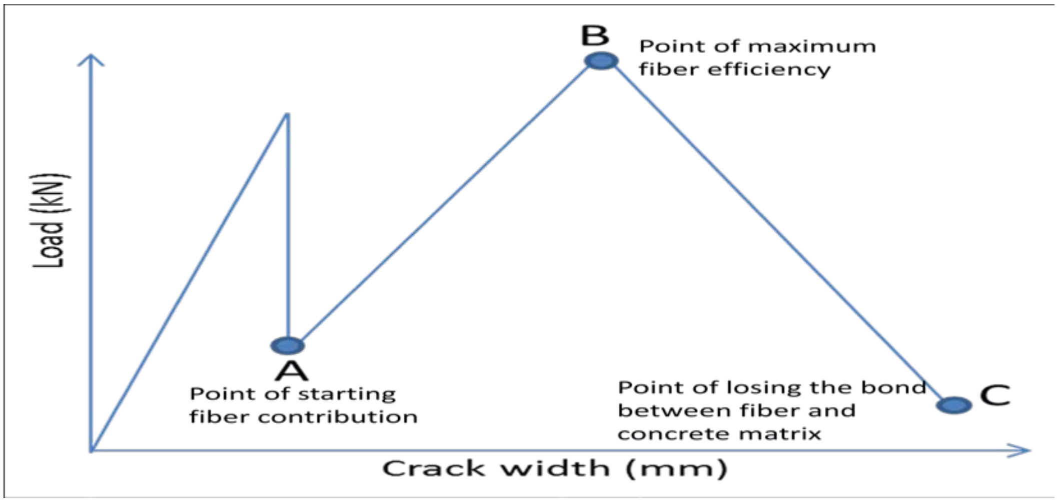
Figure 6, shows the contribution of each of the components of FR in UHPC stress-strain curve, which starts from studying concrete with fibers as superposition of three factors: matrix concrete strength, fibers efficiency strength and the interaction between both materials. After an instantaneous loss of the concrete stiffness due to cracking, the contribution of fibers begins in point A, which results in an increase in load admissible for a given crack width with regard to the slabs without fibers. The contribution of fibers grows up to point B, the moment when the fibers reach their maximum efficiency (maximum contribution). The height of point B depends on fibers content and on type of fibers. From point B downward, fibers lose the bond with concrete matrix and consequently, the fiber slide which results in reduction of internal resistance with regard to the slabs without fibers (point C).



Figure(5): Load-maximum crack width relationship

Table (4):Maximum crack width of tested slabs

Slab	Maximum crack width in service load stage	Maximum crack width in Ultimate load stage
G1Ufib0	0.25	0.34
G1Ufib0.5	0.15	0.23
G1Ufib1.1	0.12	0.2
G2Nfc40	0.18	0.26
G3Uρ1%	0.2	0.34
G4Ut55	0.69	1.47
G5Ufy560	0.27	0.31



Figure(6): Stages of load-crack width in UHPC

Energy Absorption Capacity

An approximation of the absorbed energy was carried out on the basis of the load-displacement relationships by calculating the area under this load-displacement curve in Figure 6. Table 5 shows the results of absorbed energy up to 30 mm deflection.

Table (5): Absorbed energy up to a deflection of 30 mm

Slab	Absorbed Energy (kN.mm)
G1Ufib0	1350
G1Ufib0.5	4514
G1Ufib1.1	7683
G2Nfc40	1975
G3Uρ1%	4415
G4Ut55	1875
G5Ufy560	4925

The values of energy absorption from Table 5 show that the UHPC slab with 1.1% steel fiber and conventional reinforcement (G1Ufib1.1) has energy absorption of about 5.6 times that of slab with UHPC slab without steel fiber (G1Ufib0). Also, increasing the steel fibers for UHPC from 0.5% to 1.1% definitely increases the energy absorption, that took place by 70% increasing in absorbed energy between slab G1Ufib0.5 (UHPC with 0.5% steel fiber) and slab G1Ufib1.1 (UHPC with 1.1% steel fiber). Using UHPC slab instead of NSC slab gives an increasing of energy absorption by 289%. The UHPC slabs, showed an increase in the absorption energy of 2% when the reinforcement ratio increased from 1% to 2%, which is not significant. While for UHPC, increasing the thickness of the slab from 55mm to 100mm cause an increase in absorption energy by 140%.

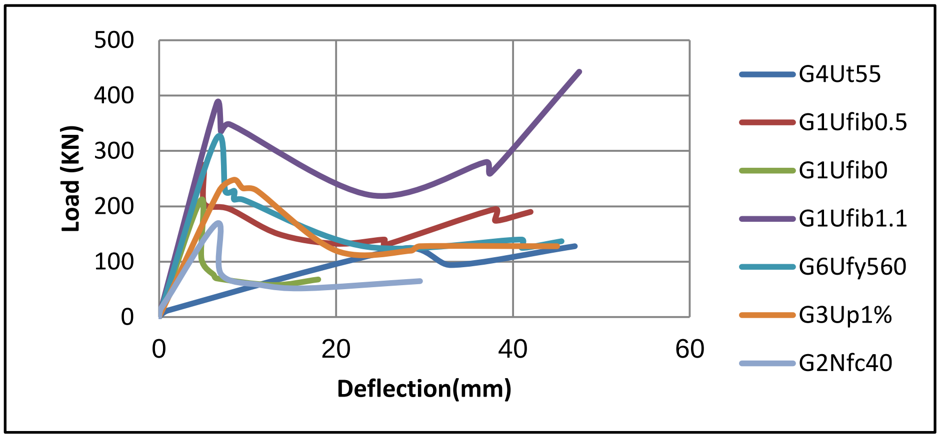


Figure (6): Load-deflection curve of tested slabs

Conclusions

- The estimation for crack spacing proposed in (10) of NSC members cannot applied to UHPC members.
- The addition of fibers to UHPC members diminishes the spacing between cracks owing to a higher transmission of stresses to concrete through adherence mechanisms.
- The contribution of the fibers to cracking in terms of crack width is significant when the amount of fibers is doubled.
- As for NSC, when doubling steel fibers in UHPC members, the crack spacing is increased by more than double.
- The crack width for UHPC slab without steel fiber at peak load is more than that of UHPC with steel fiber; this shows the efficiency of steel fiber in matrix mortar of UHPC members.
- NSC members has larger crack spacing as compared with UHPC members, this is due to aggregate interlock action in NSC.
- UHPC is considered as paste matrix material, so the addition of steel fiber will control the crack width in both service and ultimate load stage.
- A thin UHPC slab shows the higher crack width due to higher flexural behavior.

- Stages of load-crack width in UHPC, start with the action of concrete, then contribution of fiber plus concrete.
- Due to the high ductility of UHPC, the energy absorption is higher than that of NSC.

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