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The Effect of Changing the Maximum Aggregate Size on the Behavior of Reinforced Shear Key Specimens with Carbon Fiber Grid Under Direct Shear

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Keywords:

Direct Shear; Longitudinal Reinforcement; T700 Carbon Fiber Grid; Maximum Aggregate Size; Shear capacity.

Highlights:

- *ACC adapts its speed automatically to follow the vehicle ahead based on the changes in traffic conditions.*
- *Model predictive control manages different driving scenarios in real-time.*
- *The simulation was performed using MATLAB.*

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Abstract: In recent years, the use of alternative reinforcement materials in concrete members has become increasingly widespread due to their distinct properties, most notably their lightweight nature and corrosion resistance. Consequently, it has become essential to understand the behavior of structural elements reinforced with these materials and to predict their performance when subjected to various loads and stresses. In this study, a carbon fiber grid (CFG) was employed to reinforce a concrete structural member to investigate its behavior under direct shear stresses. This research aims to study the effect of changing the maximum aggregate size on the behavior of shear key specimens reinforced with CFG. The experimental study consisted of nine specimens reinforced with longitudinal T700 Carbon Fiber Grid, examining three maximum aggregate sizes, namely, 2.36, 4.75, and 9.5 mm, and three reinforcement ratios (ρ) of Max, Min, and average. After conducting the required tests, the values of shear stresses, slip, and dilation obtained from the test specimens were calculated. Additionally, the test results for these specimens were compared with each other. The results showed that at the maximum reinforcement ratio, increasing the maximum aggregate size to 9.5 mm decreased the shear capacity. Shear keys with maximum reinforcement ratio showed a decrease in the shear capacity by 27% when the maximum aggregate size increased from 2.36 to 9.5 mm.

تأثير تغيير الحد الأقصى لحجم الركام على سلوك عينات القص الرئيسية المسلحة بشبكة ألياف الكربون تحت القص المباشر

رائد مخلف رديف، سعد محمود رووف
قسم الهندسة المدنية/ كلية الهندسة / جامعة تكريت / تكريت – العراق.

الخلاصة
في السنوات الأخيرة، أصبح استخدام بدائل حديد التسليح في الاعضاء الخرسانية أكثر شيوعًا بسبب خصائصها المميزة، ولا سيما خفة وزنها ومقاومتها للتآكل. ونتيجة لذلك، أصبح من الضروري فهم سلوك الاعضاء الإنشائية المسلحة بهذه المواد والتنبؤ بأدائها عند تعرضها لأحمال واجهادات مختلفة. في هذه الدراسة، تم استخدام شبكة ألياف الكربون (CFG) لتسليح عضو انشائي خرساني لاستكشاف سلوكه تحت تأثير اجهادات القص المباشرة. تهدف هذه البحث إلى دراسة تأثير تغيير المقاس الاقصى للركام على سلوك عينات مفتاح القص المسلحة بـ CFG. تشمل الدراسة صب تسع عينات مسلحة بشبكة ألياف الكربون الطولية T700 مع استخدام ثلاث مقاسات للركام، وهي ٢,٣٦ و٤,٧٥ و٩,٥ مم، وثلاث نسب تسليح (ρ) هي الحد الأقصى، الحد الأدنى، والمتوسط. بعد إجراء الاختبارات المطلوبة، تم حساب قيم اجهادات القص، والانزلاق، والتمدد التي تم الحصول عليها من عينات الاختبار. بالإضافة إلى ذلك، تمت مقارنة نتائج الاختبار لهذه العينات مع بعضها البعض. أظهرت النتائج أنه عند أقصى نسبة تسليح، أدى زيادة المقاس الأقصى للركام إلى ٩,٥ مم إلى انخفاض في قدرة العينات على تحمل اجهادات القص، حيث أظهرت مفاتيح القص المسلحة بأعلى نسبة تسليح انخفاضًا في قدرة تحمل اجهادات القص بنسبة ٢٧٪ عندما زاد المقاس الاقصى للركام من ٢,٣٦ إلى ٩,٥ مم.

الكلمات الدالة: القص المباشر، التعزيز الطولي، شبكة ألياف الكربون T700، الحد الأقصى لحجم المجموع، قدرة القص.

1.INTRODUCTION

Concrete is typically reinforced to resist tensile stresses because its inherent tensile strength is low. These tensile stresses can be divided into two types: Those resulting from bending and those resulting from shear forces. Regarding the tensile stresses caused by shear forces, structural elements must have the capacity to withstand these stresses to ensure their integrity, which is achieved through their resistance to shear stress. Generally, the shear resistance of a structural member consists of two important factors: The shear resistance of the steel, represented by the symbol Vs, and the shear resistance of the concrete, represented by the symbol Vc. According to (ACI code 318-14) [1], determining the shear resistance of concrete is through a test called push-off specimens. Various types of specimens are used for experimental investigations into the mechanisms of shear transfer. The push-off test specimen is the most commonly employed to study the influence of direct shear stresses [2]. The shear resistance of concrete is calculated based on three fundamental variables: The compressive strength of the concrete (Vcz), the aggregate size (Viy), and the reinforcement ratio used in the region subjected to direct shear in the push-off specimen's test. Therefore, the contribution of concrete to resisting shear forces is achieved through the combination of compressive strength, aggregate interlock, and the dowel action of the main reinforcing (Vd) (ACI Code 318-19) [1]. Figure 1 illustrates the shear forces acting on a reinforced beam to resist such forces, besides the contribution of the three influencing variables on the shear resistance of concrete.

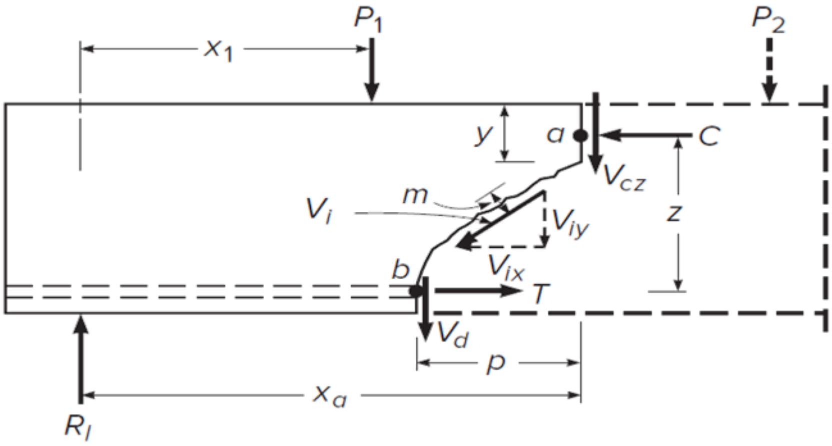


Fig. 1 Forces Acting at a Diagonal Crack in a Beam without Web Reinforcement (Birkeland, 1966) [4].

The shear resistance of concrete for any structural member can be calculated using the following equation:

$Vc = Vcz + Viy + Vd$ (ACI 318-19, 22.5.1.1)

where:

Vcz = Shear strength of concrete in the compression zone.

Viy = Interface shear due to aggregate interlock along the cracks.

Vd = Dowel action force resistance of longitudinal reinforcement.

The primary factor influencing concrete shear resistance is the dowel action of the steel reinforcement. Dowel action encompasses three distinct mechanisms, as shown in Figure 2: flexure, shear, and kinking of the steel bars. While significant levels of slip and concrete crushing are necessary to engage the reinforcement bars, dowel action alone cannot be considered the primary mechanism for shear force resistance. Excessive slip can lead to deflection problems, and the development of prominent cracks in a reinforced concrete structure can be a significant concern for its occupants. Under typical load and slip conditions, it is estimated that only 15% of the shear-friction capacity is attributed to dowel action (Paulay et al. [3]).

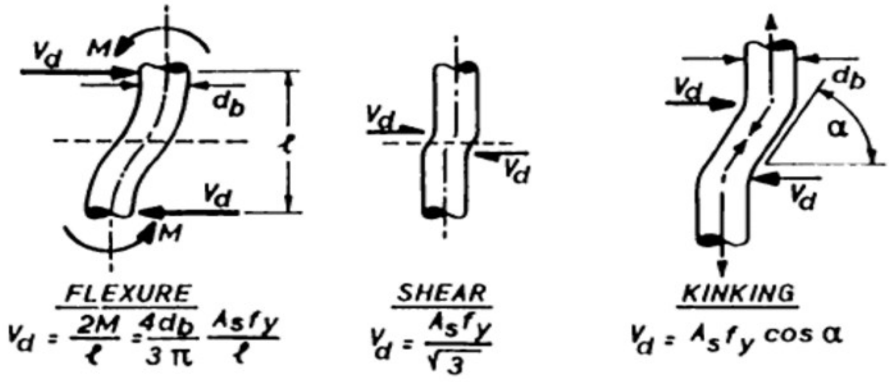


Fig. 2 Mechanisms of Dowel Action (Paulay et al. [3]).

When using normal steel reinforcement to reinforce concrete members exposed to relatively high shear forces, the contribution of the dowel force resistance of longitudinal reinforcement (Vd) is significant and effective due to the favorable properties of steel reinforcement, such as ductility. This behavior is in contrast to the shear reinforcement resistance (Viy) because of the limited interaction between concrete and steel reinforcement, resulting from the relatively large distances between steel reinforcement bars. As a result, the contribution (Viy) is relatively lower, assuming that the compressive strength of concrete is constant. Khayat and Feys [4] examined the behavior of Steel Fiber-Reinforced Concrete (SFRC) through a series of experimental tests conducted. The study of shear behavior involved monitoring crack opening and shear displacement in relation to the shear load. The study variables included the type of concrete (either Self-Compacting Concrete (SCC) or SFRC with varying fiber contents: 40 kg/m^3 or 60 kg/m^3), transverse reinforcement (TR), and the width of the pre-crack. The analysis focused on aggregate interlocking, with the findings indicating that fiber inclusion improved failure control and enhanced ductility in shear response. Shariatmadar et al. [5] experimentally examined the shear transfer behavior in reinforced concrete through the testing of pre-cracked push-off specimens. The study concentrated on the quantity of reinforcement and the application of externally bonded fiber-reinforced polymer (FRP) fabrics along the shear plane. The findings of this study detailed the shear transfer capacity and failure patterns of pre-cracked reinforced concrete push-off specimens that have been externally bonded with FRP. Al- Shathr [6] examined the behavior of self-compacting concrete (SCC) at connection points under direct shear, with a focus on carbon fiber reinforcement effects. It involved testing sixteen push-off specimens across four groups, each with different carbon fiber volume fractions and steel reinforcement parameters. The findings indicated that carbon fiber addition enhances direct shear strength. However, exclusive use of carbon fiber resulted in brittle failure, whereas incorporating rebars provided higher strain and ductility. The study determined 0.75% as the optimal carbon fiber volume fraction for both fresh and hardened concrete. Moreover, carbon fiber inclusion reduced compressive strength; however, it improved splitting tensile strength and modulus of rupture relative to reference specimens. Al-Quraishi et al. [7] experimentally and theoretically investigated the behavior of connections under direct shear, considering the influence of steel fiber reinforcement on the connections' strength and behavior. The study focused on the fiber content and the amount of shear reinforcement perpendicular to the shear plane. Data such as slip, lateral separation, and strains in the reinforcements and concrete were monitored. In the present study, Carbon Fiber Grid (CFG) is used in the reinforcement of the region exposed to shear in push-off specimens. The maximum size of the aggregate used was changed. These parameters were studied to understand the effect of changing the maximum aggregate size on the shear resistance of concrete enhanced with this type of reinforcement. Since CFG consists of multiple openings with relatively uniform sizes, the interaction or bonding with concrete is expected to be very strong. Consequently, it is anticipated that the value of (Viy) will be greater than its counterpart when using normal steel reinforcement. On the other hand, it is also expected that the value of (Vd) will be very small due to the flexible nature of the CFG. Therefore, this study aims to determine which of the two different types of reinforcement has a greater effect on improving the shear resistance of concrete (Vc). Many researchers have tested the external strengthening process using carbon fiber fabric and its effect on improving the shear resistance of concrete beams. They considered several types of carbon fiber fabric, strengthening methods, and the number of layers used. They found that using external strengthening with fibers improved the shear resistance significantly, and the improvement rates ranged from 30% to 165%. This variation is due to the type of fibers used, the number of fiber fabric layers, and the method of fixing the fibers [8-11]. To the author's knowledge, there is no available study on the performance and behavior of concrete reinforcement with Carbon Fiber Grid under direct shear conditions. This study aims to provide experimental data on the shear resistance of concrete (V_c) when employing a carbon fiber grid as the primary flexural reinforcement in structural elements. In this study, the same compressive strength value was used for all types of concrete used in casting the specimens, i.e., the concrete's shear resistance value in the compression zone (V_{cz}) remained constant. However, the value of the aggregate size used was varied, thus changing the value of shear reinforcement resistance (V_{iy}). As for the effect of dowel action (V_d), which depends on the type of reinforcement used in the push-off specimens, it will be significantly influenced. Also, it may be the primary variable affecting the calculation of the overall shear resistance of a member in this study, as it involves a new type of reinforcement called CFG. Since CFG consists of multiple openings with relatively uniform sizes, the interaction or bonding with concrete is expected to be very strong. Consequently, it is anticipated that the value of (Viy) will be greater than its counterpart when using normal steel reinforcement. Conversely, the value of (Vd) is anticipated to be quite small due to the flexible characteristics of CFG.

2.EXPERIMENTAL PROGRAM

The experimental program includes the following:

2.1.Material Properties Used in Experimental Program

Various materials, including Portland cement, fine aggregate, coarse aggregate, water, steel bars, and carbon fiber grid, were utilized to create a mixture for shear key specimens in direct shear tests. Subsequent sections detail the experimental tests performed on each material to verify its adherence to Iraqi standard specifications and ASTM standards.

2.1.1.Cement

Ordinary Portland Cement from the Tasloga factory, available in the local market, was utilized. The physical and chemical tests were conducted in the laboratories of the College of Engineering at Tikrit University. The test results for the physical and chemical properties indicated that the cement meets the Iraqi specification requirements (I.Q.S. NO. 5, 1984) [9].

2.1.2.Fine Aggregate

The study employed natural fine aggregate. The results of the sieve analysis, sulfate content, and fine materials were obtained from the tests in the Civil Engineering Laboratory at Tikrit University. A sieve size of 2.36 mm will be used to obtain the fine aggregate passing for the second mortar mixture with a Maximum Aggregate Size (M.A.S) of 2.36 mm. The test outcomes met the requirements of the Iraqi standard specifications (I.Q.S. No. 45, 1984) [10].

2.1.3.Coarse Aggregate

For the concrete mixture preparation, a coarse aggregate with a maximum size of 9.5 mm was utilized. The sieve analysis results, along with the coarse aggregate's sulfate content and fine materials, were performed at Tikrit University's Civil Engineering Department. These test outcomes complied with the Iraqi Specification (I.Q.S. No. 45, 1984) [10] requirements.

2.1.4.Water

Ordinary tap water was utilized for the mixing and curing processes.

2.2.Design of Concrete Mixtures Design

Concrete mixes were designed to select suitable proportions of the mix ingredients that satisfy the required compressive strength of 40 MPa according to the ACI code (ACI-2019) [1] with a normal coarse aggregate of 9.5mm. The proportions of this mix are shown in Table 1.

2.3.Reinforcements

2.3.1.Carbon Fiber Grid

One type of carbon fiber grid (CFG) materials, namely T(700), were utilized. The CFG geometry was an open-mesh measuring 20×20mm, with roving evenly distributed equally in two perpendicular directions. The fiber details employed are provided in Table 2.

Table 1 Proportions of Mixture Design.

Mix No.	Proportions	Cement (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	W/c (kg/m³)	W/c (%)
1	1:1.63:2.10	445	725	935	205	46

Table 2 Typical Properties of by Product Materials.

Nominal thickness (mm)	Weight (g/m²)	Mesh size (mm)	Tensile strength (MPa)	Elastic Modulus (GPa)
0.095	160	20*20	4300	>228

2.4.Strain Gauge

A strain gauge is a device used to measure the strain or deformation of an object. The sensor converts mechanical displacement or strain into an electrical signal. Strain gauges are commonly used in various applications, such as stress analysis, load measurement, and force sensing. Oasis Technology, Inc., manufactured the strain gauge, and Tokyo Measuring Instruments Lab manufactured the epoxy adhesive and SB tape for protection and coating materials, as shown in Figure 3. The properties of the strain gauge, adhesive materials, SB tape, and coating material (W-1), according to the manufacturer's datasheet, are shown in Table 3.

2.5.Molds Preparations

The 9-shear key specimens were cast using wooden molds. Three molds were prepared, with three specimens cast for each of the three mixtures. The dimensions of the molds were 600 mm in height, 300 mm in width, and 150 mm in depth (Wermager et al. [2]), as illustrated in Figure 4.

2.6.Details of Specimens

The present study used nine shear key specimens with dimensions of 600 × 300 × 150 mm (height, width, and depth, respectively). Table 4 shows the specimen matrix. These samples were divided into three groups, each containing three samples, according to the type of mixtures used. The first mixture was a cement mortar with a maximum size of 2.36 mm. The second mixture was a cement mortar with a maximum aggregate size of 4.75 mm. The third mixture was normal concrete with a maximum aggregate size of 9.5 mm. Each group included one model reinforced with CFG type (T700), with three reinforcement ratios: ρ_{min}, ρ_{av}, and ρ_{max}. These specimens were tested in a direct shear test (Push-off Test). The shear plane area for the shear key models was 32,400 mm², with the reinforcement ratios chosen as 0.009, 0.016, and 0.022. All details are shown in Table 4 and Figure 5. All mixture components were prepared using an electronic balance in the graduate laboratory at Tikrit University's College of Engineering. Two types of laboratory mixers were utilized to mix the components for two varieties of cement mortar and one type of normal concrete. All wooden molds were primed and oiled, and the reinforcement of shear key specimens was arranged within them, as illustrated in Figs. 6 and 7. The casting process involved filling the molds with the mixture and compacting the samples with a mechanical vibrator. After pouring, the concrete and the top surfaces of all main shear key specimens were smoothed with a hand steel trowel, as indicated in Figure 8. Then, a groove was made on the upper surface of the direct shear zone, as shown in Figure 9, corresponding to the incision on the lower surface that was initially installed in the model. These cracks are useful to force the crack into the design location of the specimens. Samples were demolded 24 hours post-casting and subsequently water-treated. Finally, all specimens were painted white to enhance the crack formation and growth visibility during tests, as shown in Figure 10.

Fig. 3 Steel Strain Gauge Used in the Current Study.

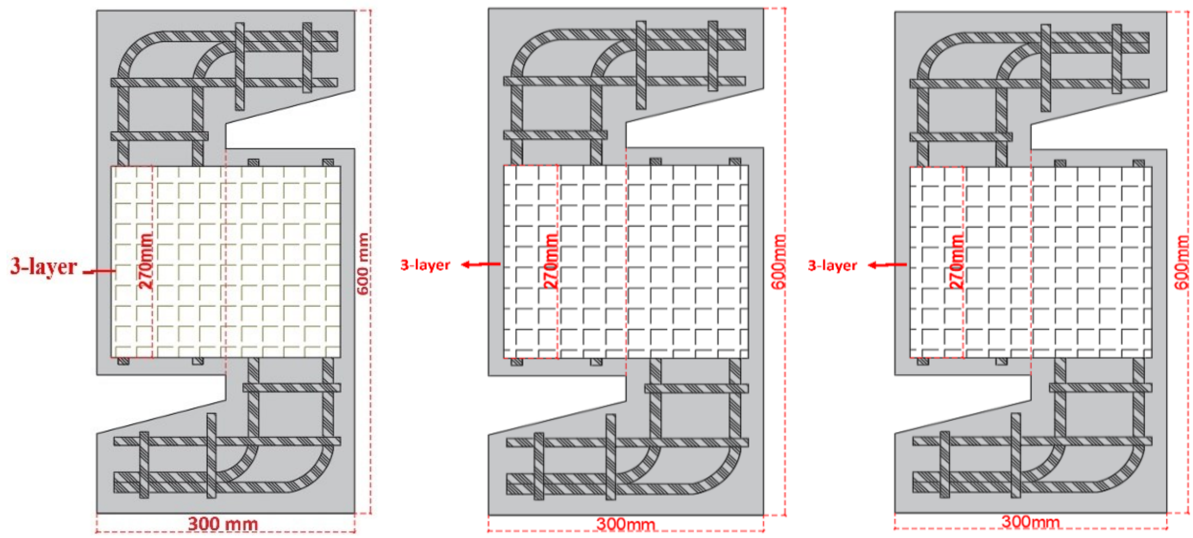
Table 3 Properties of the Steel Strain Gauge Used in the Current Study According to the Manufacturer's Data.

Strain gauge name	**No.**	**1**	**2**	**3**	**4**	**5**	**6**
BF120-5AA	Details	Gauge (Length * width)	Gauge base length	Gauge resistance	Sensitivity coefficient	Wire length	Transverse sensitivity
Steel – one direction	Description	5 mm* 2mm	9.6 mm × 4 mm	120/350 ± 0.1Ω	2.08 ± 1% (A level)	2.5 meter	-0.6%

Fig. 4 The Wooden Molds Used in the Present Study.

Table 4 Specimens Matrix Details.

Mix Type	**Mortar 2.36 mm**			**Mortar 4.75 mm**			**Normal Concrete 9.5 mm**		
Reinforcement ratio(ρ)	0.009	0.016	0.022	0.009	0.016	0.022	0.009	0.016	0.022
Specimen ID	M2-7	M2-8	M2-9	M4-7	M4-8	M4-9	NC-7	NC-8	NC-9



ρ_{min}(M2-9, M4-9,NC-9) ρ_{ava},(M2-8,M4-8,NC-8) ρ_{max}(M2-7, M4-7,NC-7)

Fig. 5 Details of All Specimens' Reinforcement.

Fig. 6 Reinforcement of the Shear Key Specimens.

Fig. 7 Preparation of Molds and Reinforcement Placed in the Molds of the Shear Key Specimens.

Fig. 8 Casting, Vibrator for Compact, and Finished the Surface by Hand Steel Trowel of the Shear Key Specimens.

Fig. 9 Making a Groove in Specimens after Refining the Top Face.

Fig. 10 Painted shear key specimens.

2.7.Test Setup

A universal testing machine (UTM), specifically a SANS model, with a capacity of 2000 kN, was utilized for the test. The load was applied at a rate of 1.5 kN/sec. The specimens underwent two-point loading. The force exerted was measured using a load cell, accompanied by six LVDTs. Two LVDTs were placed on the right and left, and touch the top and bottom. They were used to measure the vertical displacement (slip) of the specimens, and four LVDTs were placed, two for each face, and installed on the specimen to measure the crack width (dilation). A data logger with 16 channels was used to collect data from the test, as shown in Figs. 11 and 12.

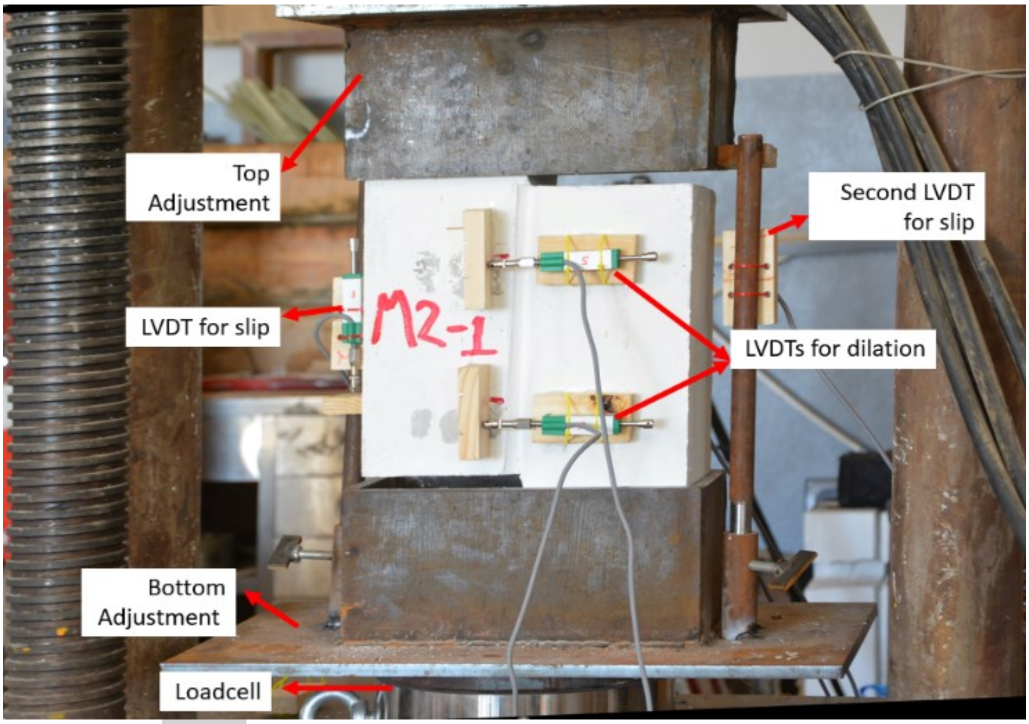


Fig. 11 Load and Deflection Monitoring by the Data Logger.

Fig. 12 Load and Deflection Monitoring by the Data Logger.

3.EXPERIMENTAL RESULTS

This section presents information regarding the shear key specimens with longitudinal T700 Carbon Fiber Grid, which has an ultimate tensile strength of 4307 MPa and modulus of elasticity of 232 GPa, tested in this work. As discussed previously in 13, nine specimens were investigated, with three maximum aggregate sizes, namely 2, 4, and 9 mm, and three longitudinal T700 Carbon Fiber Grid ratios ρ of Max, Min, and average.

3.1.Specimens with Min Reinforcement Ratio (ρ = ρmin)

The results of testing the shear key specimens with longitudinal T700 Carbon Fiber Grid reinforcement with a reinforcement ratio of 0.009 are presented in Fig. 13. All specimens showed a failure along the critical shear plane.

(a) (b) (c)

Fig. 13 Shear Plane Crack of Specimens with Minimum Reinforcement (a) Maximum Aggregate Size of 2 mm, (b) Maximum Aggregate Size of 4 mm, and (c) Maximum Aggregate Size of 9 mm.

As shown in Fig. 14, the shear resistance of the examined specimens noticeably increased with the increase of maximum aggregate size in the used concrete. The shear key with a maximum aggregate size of 9 mm resisted a shear force of 290 kN, compared to 256 and 206 kN for specimens with maximum aggregate sizes of 4 and 2 mm, respectively, which represent an increase of 13% and 41%, respectively. This behavior was expected and attributed to the larger contribution of the aggregate interlock factor (V_{iy}) in the total concrete shear capacity (V_c). In terms of the slip at the ultimate shear, it was almost similar for all examined specimens with different maximum aggregate sizes. This behavior is attributed to the similarity in the kinking deformations due to the similarity in the stiffness of the T300 Carbon Fiber Grid reinforcement. As for the ductility of the examined specimen with minimum longitudinal T700 Carbon Fiber Grid reinforcement, the results showed a low ductility, where the specimen with maximum aggregate size of 9 mm maintained zero shear capacity at slip of 1.4 mm and lost about 60% of the ultimate shear capacity after a slip of 1 mm only. Specimens with 4 and 2 mm maximum aggregate size lost their full shear capacity after 1.3 mm slip only. This lack of ductility is fully attributed to the brittle nature of the T700 Carbon Fiber Grid reinforcement, which cannot endure any deformations after the yielding point, unlike the other ductile materials.

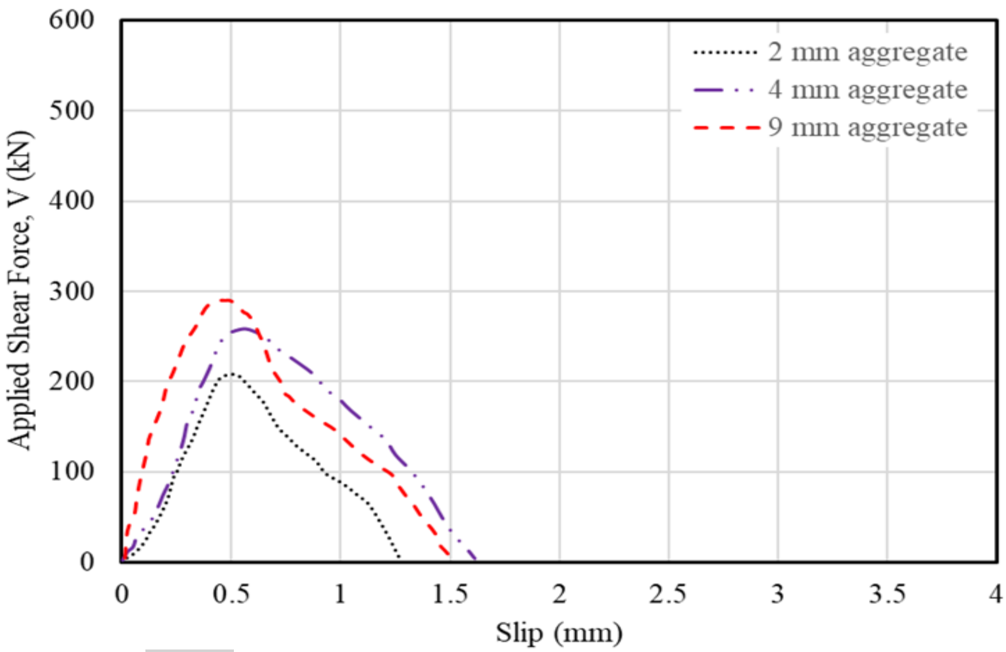


Fig. 14 Shear Force vs. Vertical Slip for Specimens with ρ_{min}.

A similar trend was noticed with the crack width versus the applied shear force, as shown in Fig. 15, which represents the horizontal crack width (Dilation) versus the applied shear force. The relation was almost linear before and after the peak shear capacity due to the fully elastic nature of the T700 Carbon Fiber Grid reinforcement. Since all of the examined specimens in this group had the same amount of longitudinal T700 Carbon Fiber Grid reinforcement with the same stiffness, both the dilation at the ultimate shear force and the slope of the curve were almost identical. In addition, the ductility was very low as mentioned before. Figure 16 represents the relation between the slip and dilation. Due to the brittle and elastic nature of the T700 Carbon Fiber Grid reinforcement, this figure shows that as the slip increased, the horizontal crack width increased, representing the crack, until a crack width of 1.4 mm was recorded for a specimen with a 9 mm maximum aggregate size. At this level of dilation, all of the specimens showed a slip range from 1.1 mm in a specimen with a 2 mm maximum aggregate size until 1.6 mm with a specimen with 4 and 9 mm maximum aggregate size, before full collapse due to the lack of ductility in the T700 Carbon Fiber Grid reinforcement, as shown in Fig. 16.

3.1.1.Specimens with Average Reinforcement Ratio (ρ = ρaverage)

The results of testing the shear key specimens with longitudinal T700 Carbon Fiber Grid reinforcement with a reinforcement ratio of 0.016 are presented in Fig. 17. All specimens showed a failure along the critical shear plane.

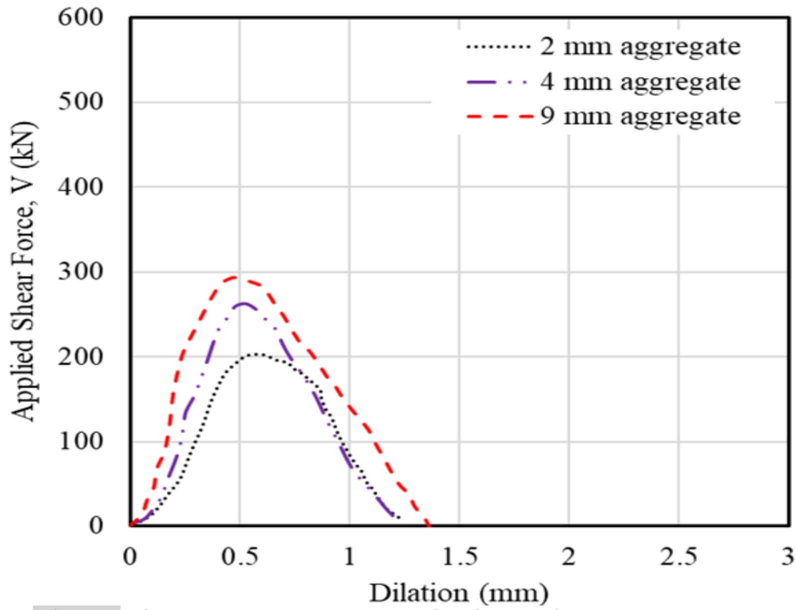


Fig. 15 Shear Force vs. Horizontal Dilation for Specimens ρ_{min}.

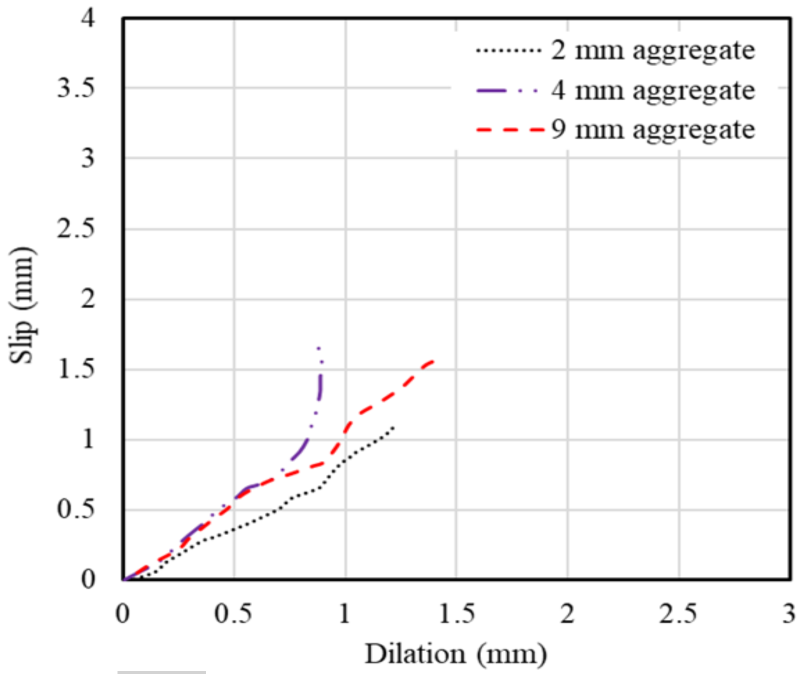


Fig. 16 Slip vs. Dilation for Specimens with ρ_{min}.

(a) (b) (c)

Fig. 17 Shear Plane Crack of Specimens with Average Reinforcement (a) Maximum Aggregate Size of 2 mm, (b) Maximum Aggregate Size of 4 mm, and (c) Maximum Aggregate Size of 9 mm.

Unlike the previous case, in this case, with even the average reinforcement ratio, specimens with a maximum aggregate size of 2 mm showed the highest shear resistance capacity, which contradicts the assumption or the hypothesis that a higher or larger maximum aggregate size results in higher shear capacity. This phenomenon can be attributed to the heavily reinforced crowded zone at the critical shear section that totally prevented the aggregate from interfering in the critical zone and worked almost as a sieve to prevent large particles from going inside. In addition, the encapsulation around the T700 Carbon Fiber Grid, which has a direct connection to the bond, was affected as well. As a result, this produced less capacity for a specimen with concrete that has a relatively larger aggregate size. As shown in Fig. 18, the shear resistance of the test specimens was increased with the decrease of maximum aggregate size in the used concrete. The shear key with a maximum aggregate size of 2.36 mm resisted a shear force of 359 kN, compared to 272 and 227 kN for specimens with maximum aggregate sizes of 4.75 and 9.5 mm, respectively, representing decreases of 24% and 37%, respectively. This behavior is attributed to the prevention of the aggregate from entering the critical zone due to the high reinforcement, which reduced the contribution of the interlock factor (V_{iy}) in the total concrete shear capacity (V_c). It is worth mentioning that the effect of high reinforcement was more pronounced with T700 Carbon Fiber Grid reinforcement than steel rebars due to the small size of the opining in both directions of the grid of 10 mm, in addition to the overlap with other layers that may produce smaller grid size that can work as a sieve to prevent large particles from being normally distributed in the critical shear plane. In terms of the slip at the ultimate shear, it was almost similar for all examined specimens with different maximum aggregate sizes. This behavior is attributed to the similarity in the amount of T700 Carbon Fiber Grid reinforcement, which resulted in the same amount of kinking deformations due to the similarity in the stiffness of the T700 Carbon Fiber Grid reinforcement. As for the ductility of the examined specimen with average longitudinal T700 Carbon Fiber Grid reinforcement, the results showed a low ductility, where the specimen with a maximum aggregate size of 2 mm maintained zero shear capacity at a slip of 1.8 mm, and it lost about 48% of the ultimate shear capacity after a slip of 1 mm only. Specimens with 4 and 9 mm maximum aggregate size lost their full shear capacity after 2.2- and 1.2-mm slip only. This lack of ductility is fully attributed to the brittle nature of the T700 Carbon Fiber Grid reinforcement, which cannot endure any deformations after the yielding point, unlike the other ductile materials. A similar trend was noticed with the crack width versus the applied shear force, as shown in Fig. 19, which represents the horizontal crack width (Dilation) versus the applied shear force. The relation was almost linear before and after the peak shear capacity due to the fully elastic nature of the T700 Carbon Fiber Grid reinforcement. Since all of the examined specimens in this group had the same amount of longitudinal T700 Carbon Fiber Grid reinforcement with the same stiffness, both the dilation at the ultimate shear force and the slope of the curve were almost identical. In addition, the ductility was very low as mentioned before.

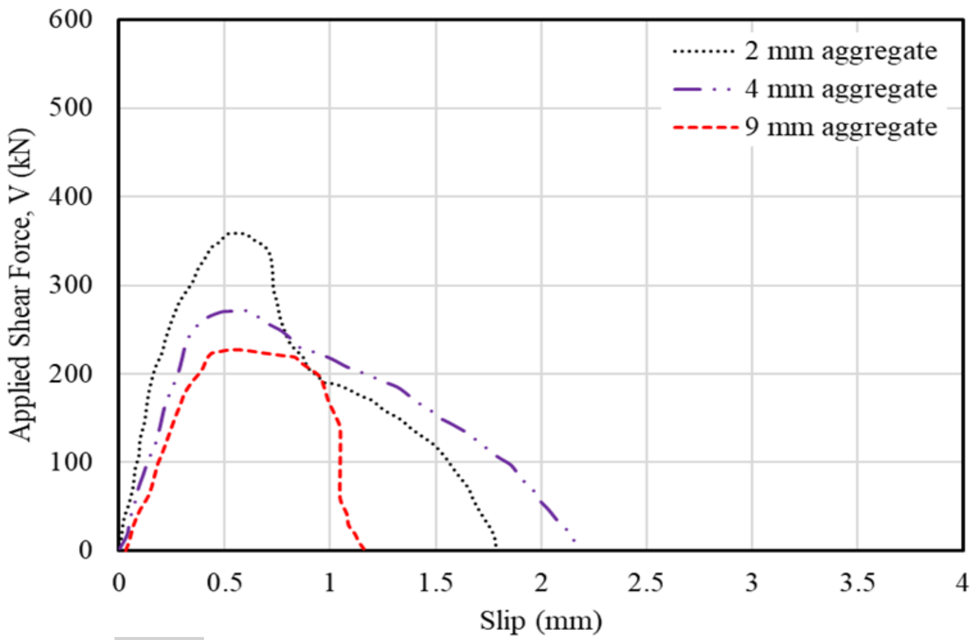


Fig. 18 Shear Force vs. Vertical Slip for Specimens with $\rho_{average}$.

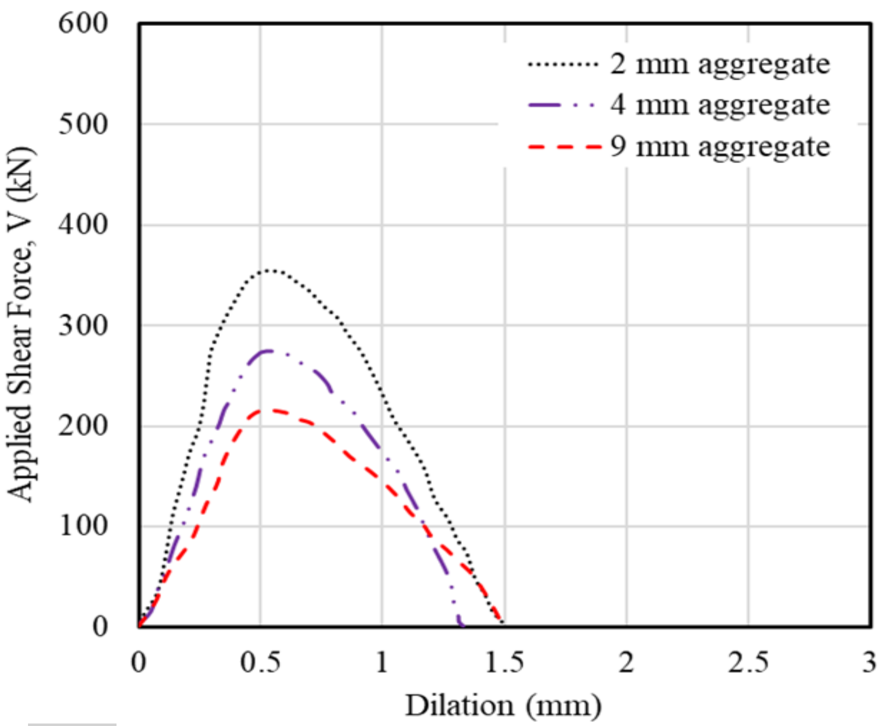


Fig. 19 Shear Force vs. Horizontal Dilation for Specimens with $\rho_{average}$.

Figure 20 represents the relation between the slip and dilation. Due to the brittle and elastic nature of the T700 Carbon Fiber Grid reinforcement, this figure shows that as much as the slip increased, the dilation, which represents the horizontal crack width, increased until a crack width of 1.5 mm was recorded for specimens with 2, 4, and 9 mm maximum aggregate size. At this level of dilation, all of the specimens showed a slip range from 2.2 mm in a specimen with a 4 mm maximum aggregate size to 1.2 mm in a specimen with a 9 mm maximum aggregate size, before full collapse due to the lack of ductility in the T700 Carbon Fiber Grid.

3.1.3.Specimens with Max Reinforcement Ratio (ρ = ρmax)

The results of testing the shear key specimens with longitudinal T700 Carbon Fiber Grid reinforcement with a reinforcement ratio of 0.022 are presented in Fig. 21. All specimens showed a failure along the critical shear plane.

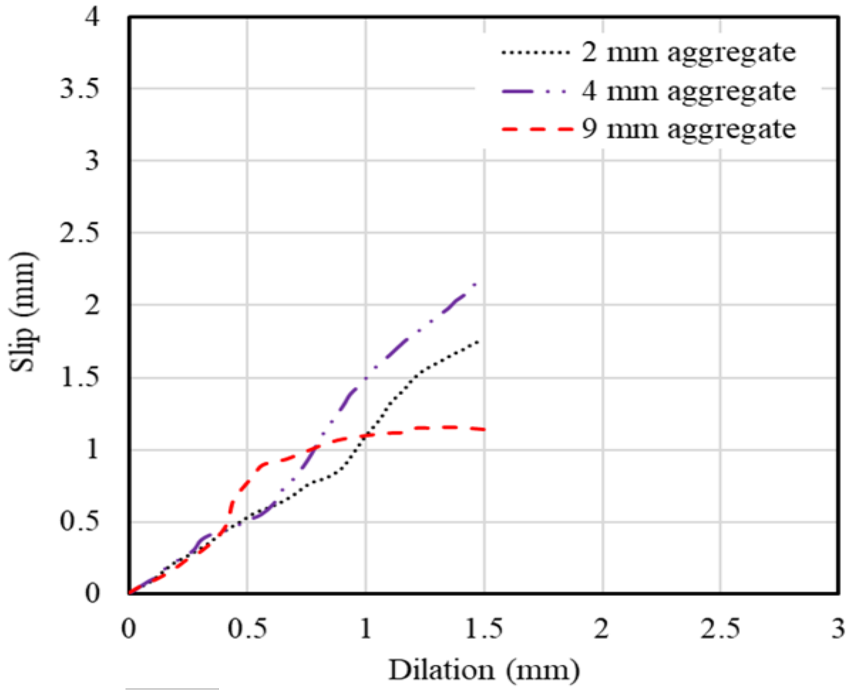


Fig. 20 Slip vs. Dilation for Specimens with $\rho_{average}$.

(a) (b) (c)

Fig. 21 Shear Plane Crack of Specimens with Reinforcement (a) Maximum Aggregate Size of 2 mm, (b) Maximum Aggregate Size of 4 mm, and (c) Maximum Aggregate Size of 9 mm.

Similar to the previous case with ($\rho_{average}$), in this case with the maximum reinforcement ratio, specimens with a maximum aggregate size of 2 mm showed the highest shear resistance capacity, which contradicts the assumption or the hypothesis that a higher or larger maximum aggregate size results in higher shear capacity. This phenomenon can be attributed to the heavily reinforced crowded zone at the critical shear section, which, even more than the previous case, prevented the aggregate from interfering in the critical zone totally and worked almost as a sieve to prevent large particles from going inside. In addition, the encapsulation around the T700 Carbon Fiber Grid, which has a direct connection to the bond, was affected as well. As a result, this behavior produced less capacity for a specimen with concrete that has a relatively larger aggregate size. As shown in Fig. 22, the shear resistance of the examined specimens increased with the decrease of maximum aggregate size in the used concrete. The shear key with a maximum aggregate size of 2 mm resisted a shear force of 408 kN, compared to 329 and 199 kN for specimens with maximum aggregate sizes of 4 and 9 mm, respectively, which represents a decrease of 19% and 51%, respectively. This behavior was attributed to the prevention of the aggregate from entering the critical zone due to the high reinforcement, which reduced the contribution of the interlock factor (V_{iy}) in the total concrete shear capacity (V_c). The effect of high reinforcement was more pronounced with T700 Carbon Fiber Grid reinforcement, with a maximum reinforcement ratio than the average reinforcement ratio. This behavior is due to the small size of the opening in both directions, with the multiple overlaps with other layers that may produce a smaller grid size, i.e., can work as a sieve to prevent large particles from being normally distributed in the critical shear plane. In terms of the slip at the ultimate shear, it was almost similar for all examined specimens with different maximum aggregate sizes. This behavior is attributed to the similarity in the amount of T700 Carbon Fiber Grid reinforcement, which resulted in the same amount of kinking deformations due to the similarity in the stiffness of the T700 Carbon Fiber Grid reinforcement. As for the ductility of the examined specimen with average longitudinal T700 Carbon Fiber Grid reinforcement, the results showed a low ductility compared to specimens reinforced with steel bars, where the specimen with maximum aggregate size of 2 mm maintained zero shear capacity at slip of 2.7 mm, and lost about 60% of the ultimate shear capacity after a slip of 1.5 mm only. Specimens with 4 and 9 mm maximum aggregate size lost their full shear capacity after 1.8- and 0.95-mm slip only. This lack of ductility is fully attributed to the brittle nature of the T700 Carbon Fiber Grid reinforcement, which cannot endure any deformations after the yielding point, unlike the other ductile materials. A similar trend was observed with the crack width versus the applied shear force, as shown in Fig. 23, which represents the horizontal crack width (Dilation) versus the applied shear force. The relation was almost linear before and after the peak shear capacity due to the fully elastic nature of the T700 Carbon Fiber Grid reinforcement. Since all of the examined specimens in this group have the same amount of longitudinal T700 Carbon Fiber Grid reinforcement with the same stiffness, both the dilation at the ultimate shear force and the slope of the curve were almost identical. In addition, the ductility was very low as mentioned before. Figure 24 represents the relation between the slip and dilation. Due to the brittle and elastic nature of the T700 Carbon Fiber Grid reinforcement, this figure shows that as much as the slip increased, the dilation, which represents the horizontal crack width, increased until a crack width of 1.8 mm was recorded for the specimen with a 2 mm maximum aggregate size. At this level of dilation, all of the specimens showed a slip range from 2.5 mm in a specimen with a 2 mm maximum aggregate size to 1 mm in a specimen with a 9 mm maximum aggregate size, before full collapse due to the lack of ductility in the T700 Carbon Fiber Grid reinforcement.

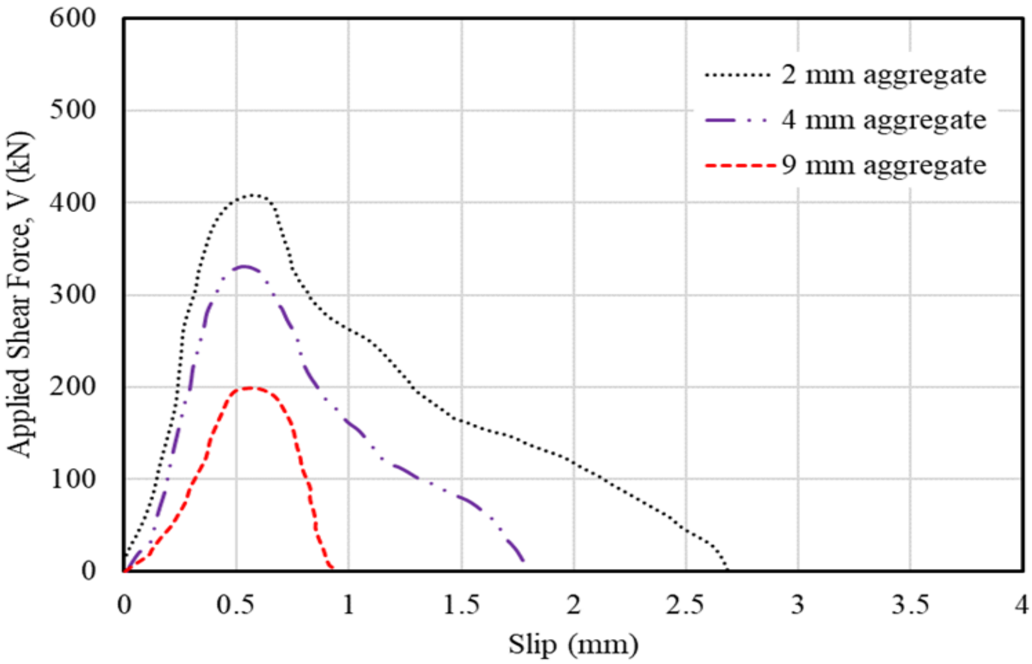


Fig. 22 Shear Force vs. Vertical Slip for Specimens with ρ_{max}.

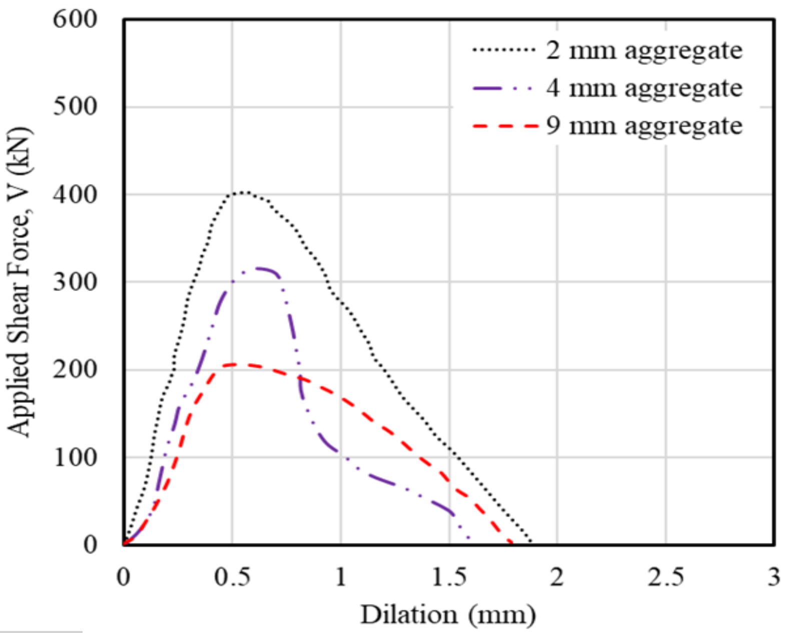


Fig. 23 Shear Force vs. Horizontal Dilation for Specimens with ρ_{max}.

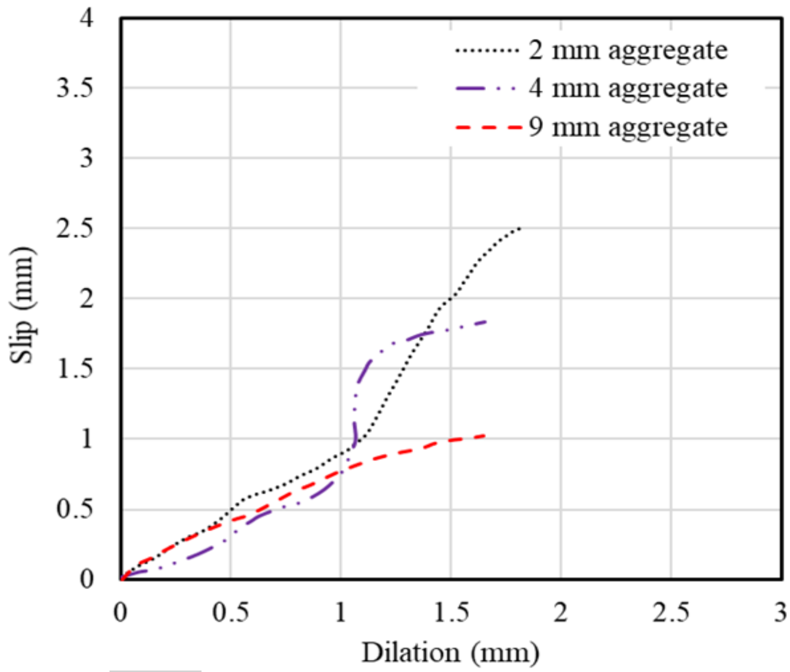


Fig. 24 Slip vs. Dilation for Specimens with ρ_{max}.

3.2.Effect of Reinforcement Ratio

Figure 25 compares the different reinforcement ratios that were examined in this study. Figure 25 presents the shear capacity of all examined specimens reinforced with different maximum aggregate sizes and reinforcement ratios. As shown in all figures, increasing the reinforcement ratios increased the shear capacity of the tested specimens only in the case of the relatively small aggregate size of 2 mm, while decreasing the shear capacity in the case of specimens with 4 and 9 mm maximum aggregate sizes. A small aggregate size of 2 mm highlighted the effect of increasing the reinforcement ratio for carbon fiber. However, with a relatively large aggregate size of 9 mm, increasing the reinforcement ratio decreased the shear capacity because the large aggregate particles could not reach the critical shear plane due to the small spacing between the steel bars of the carbon fiber grids, as was explained before. For example, shear keys reinforced with CFG showed an improvement in the shear capacity of 50% when the reinforcement ratio was increased from min to max with a maximum aggregate size of 2 mm (Fig. 25). However, with a maximum aggregate size of 9 mm, the shear capacity decreased by 10% when the reinforcement ratio was increased from min to max due to the reason explained before.

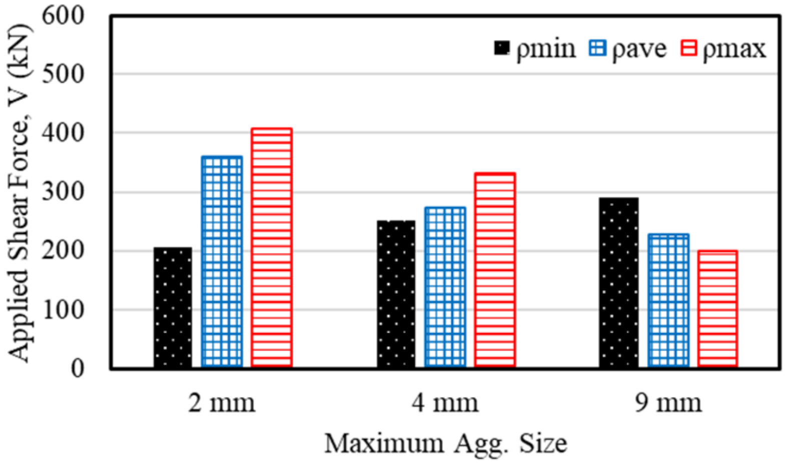


Fig. 25 Shear Capacity of All Examined Specimens with different Maximum Aggregate Sizes and Reinforcement Ratios.

3.3.Effect of Aggregate Size

Figure 26 compares all of the examined shear keys with different maximum aggregate sizes of 2-, 4-, and 9-mm with different reinforcement ratios used in this study by presenting the shear capacity of all examined specimens reinforced with T700 Carbon Fiber Grid reinforcements with different reinforcement ratios. As shown in Fig. 26, at the maximum reinforcement ratio, increasing the maximum aggregate size to 9 mm decreased the shear capacity. For example, shear keys with maximum reinforcement ratio showed a decrease in the shear capacity of 27% when the maximum aggregate size increased from 2 to 9 mm. The reason behind this significant difference in the shear capacity was attributed to the heavily reinforced crowded zone at the critical shear section, which totally prevented the aggregate from interfering in the critical zone and worked almost as a sieve to prevent large particles from going inside. In addition, the encapsulation around the steel bars, which has a direct connection to the bond, was affected as well. As a result, this produced less capacity for a specimen with concrete that has a relatively larger aggregate size. This behavior eliminated the aggregate interlocking factor (V_{iy}) for the shear capacity equation and resulted in a smaller shear capacity value (V_c).

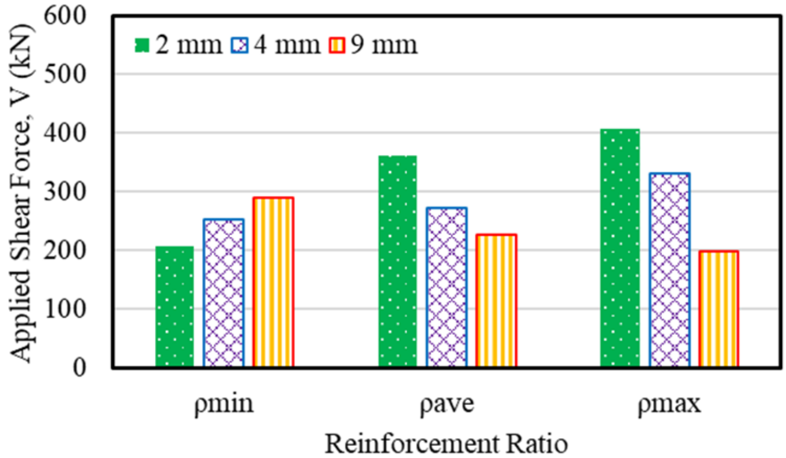


Fig. 26 Shear Capacity of All Examined Specimens with different Maximum Aggregate Sizes and Reinforcement Ratios.

4.CONCLUSIONS

The main conclusions of the present study are as follows:

1- Increasing the maximum aggregate size contributed positively to increasing the shear capacity when the reinforcement ratio was at the minimum. However, by increasing the reinforcement ratio to the maximum, the sheer capacity decreased with increasing the maximum aggregate size. This behavior can be attributed to the small spacing available in the critical shear plane, which prevented the large aggregate particles from reaching or distributing very well in the critical section. This result was even more precise with the two types of carbon fiber that have a grid size of 20 mm, which acted as a sieve to prevent large particles from entering the critical zone.

2- Regarding the stiffness and the crack opening of all of the specimens, all of them always maintained the same slope until the peak shear capacity. This behavior can be attributed to the similarity in the modulus of elasticity of all the types of reinforcement used.

3- Increasing the reinforcement ratio from the minimum to the maximum increased the shear capacity when the maximum aggregate size was 2 mm. However, using a maximum aggregate size of 9 mm, the capacity decreased with the increase of the maximum reinforcement ratio.

REFERENCES

[1] American Concrete Institute (ACI). **Design and Construction Guide of Externally Bonded FRCM System for Concrete and Masonry Repair and Strengthening (ACI 549)**. American Concrete Institute; 2019.

[2] Wermager SL. **Shear-Friction of Sand-Lightweight Clay and Slate Aggregate Concretes with Varied Reinforcement Ratios**. Master's Thesis, University of Nebraska-Lincoln; 2015.

[3] Paulay T, Park R, Phillips MH. **Horizontal Construction Joints in Cast-in-Place Reinforced Concrete**. *American Concrete Institute, ACI Special Publication* 1974**; SP-042**: 599–616.

[4] Khayat KH, Feys D. **Design, Production and Placement of Self-Consolidating Concrete**. *RILEM Bookseries* 2010; **1**: 429–438.

[5] Shariatmadar H, Khatamirad M, Zamani E. **Pre-Cracked Concrete Shear Strengthened with External CFRP Strips**. *Journal of Rehabilitation in Civil Engineering* 2013; **1**(1): 29–38.

[6] Al-Shathr BS, Al-Attar TS, Hasan ZA. **Effect of Curing System on Metakaolin Based Geopolymer Concrete**. *Journal of Babylon University* 2016; **24**(3): 569-576.

[7] Al-Quraishi H, Lafta MJ, Abdulridha AA. **Direct Shear Behavior of Fiber Reinforced Concrete Elements**. *Journal of Engineering* 2018; **24**(1): 231–248.

[8] Birkeland PW, Birkeland HW. **Connections in Precast Concrete Construction**. *ACI Journal Proceedings* 1966; **63**(3): 345-368.

[9] Iraqi Specification No. 5. **Portland Cement**. Central Agency for Standardization and Quality Control, Planning Council, Baghdad, Iraq; 1984.

[10] Iraqi Specification No. 45. **Aggregate from Natural Sources for Concrete and Construction**. Central Agency for Standardization and Quality Control, Planning Council, Baghdad, Iraq; 1984.

[11] Salih YA, Al-Salman HA, Jomaa'h MM, Abdulla AI. **Flexural Behavior of Reinforced Concrete Voided Slabs Strengthened with Different Types of FRP: State-of-the-Art Review**. *Tikrit Journal of Engineering Sciences* 2023; **30**(3): 124-139.