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Shear capacity of composite beams using numerous bolted shear connectors under static loads

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Abstract:

The structural system, which consists of composite slabs and steel beams, is considered an ideal structural architectural solution. It provides flexibility in the spans and reduces the dimensions of the structural elements. The shear connector is the most important part of composite beams. Moreover, the shear studs
welded with the upper flange of the steel section are the most common. Several studies have focused on replacing these studs with a more efficient and effective type. Among them, a new technology called UPC has been introduced in Spain. This technology creates a complete shear connection, by forming small crown-shaped pieces into the steel sheeting, as an alternative to the usual embossing system in composite slabs. This paper tests the shear capacity of a new shear connector similar to the UPC technique to use in composite beams. The new shear connector is four steel angles fixed by bolts and looks like a crown. The push test was modeled with the new crown connector by Abaqus software. The failure modes were studied. The relationship between the force and slip was drawn for different concrete grades. The analytical model has been verified by comparing it with the results of previous studies conducted on different shear connectors. This paper introduces the idea of creating shear connectivity by using semi crown-shaped that could replace the old technology using welded studs. As result, the crown shear connector, which was made up of four bolted metal angles, provided a high shear capacity and could be used in place of welded studs. Furthermore, the crown shear connector demonstrated ductility when C58 concrete was used.

Keywords: Composite Beams, Shear Connectors, Push-Out Test.

قدرة القص للجوائز المختلطة باستخدام العديد من موصلات القص المثبتة بالبراغي تحت الأحمال الساكنة

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الملخص:

يشكل موصل القص العنصر الاهم في الجوائز المختلطة وتعتبر المسامير الملحومة أكثر موصلات القص انتشارا. ركزت العديد من الدراسات على استبدال مسامير القص الملحومة بموصلات قص أكثر كفاءة وفعالية، من بينها دراسة في اسبانيا قدمت تكنولوجيا جديدة سميتUPC تخلق هذه التقنية اتصال قص كامل في البلاطات المختلطة، من خلال تشكيل قطع صغيرة على شكل تيجان في الصفائح الفولاذية، كبديل لنظام النقش المعتاد في البلاطات المختلطة. يختبر هذا البحث قدرة القص لموصل قص جديد يحاكي تقنية UPC ذات الفعل القصي السطي لاستخدامه في الجوائز المختلطة. موصل القص الجديد عبارة عن أربع زوايا فولاذية مثبتة ببراغي تشكل مع بعضها ما يشبة التاج.

تم نمذجة اختبار push out باستخدام موصل القص التاجي الجديد بواسطة برنامج Abaqus للتحقق من مقدرته القصية. تمت دراسة انماط الانهيار. كما تم رسم العلاقة بين القوة والانزياح من أجل مقاومات مختلفة من الخرسانة. تم التحقق من النموذج التحليلي بمقارنته بنتائج دراسات سابقة أجريت على موصلات قص مختلفة. يقدم هذا البحث فكرة إنشاء اتصال قص سطحي باستخدام موصل قص جديد يشبه التاج يمكن أن يحل محل التقنية القديمة التي تستخدم المسامير الملحومة. أظهر موصل القص التاجي المقترح قدرة قص عالية. كما أظهر موصل القص التاجي مطاوعة عند استخدام الخرسانة C58

الكلمات المفتاحية: الجوائز المختلطة، موصلات القص، اختبار push out.

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Introduction

In composite beams, the shear connector ensures the transfer of shear forces between the reinforced concrete slab and steel profile. Shear connectors are designed to resist longitudinal shear forces generated on the surface of reinforced concrete slabs. Due to their high automation, speed, and ease of laying, welded studs are the most commonly used shear connectors. However, their high costs, high equipment costs, and low economic feasibility in residential construction limit their use in our local markets. In addition, Several types of shear connectors have been developed in composite beams to provide a competitive alternative to studs such as Superposed Perfobond Connectors[5], bolt shear connectors [9], and angle shear connectors [10]. Tahmasbi, Maleki, Shariati, Ramli, & Tahiri (2016) [10] Studied the behavior of C and L-shaped shear connectors embedded in solid concrete slabs. Eight specimens with angle shear connectors were manufactured and tested by push test following EC4 conditions.

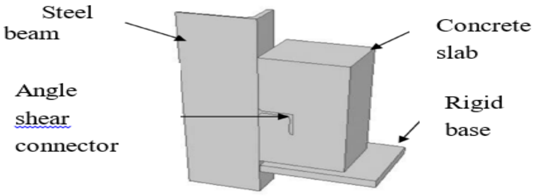

Fig (1) Model of push-out test specimen[10]

Also, a finite element model was made using the Abaqus software. The researchers concluded that increasing the length of the shear connectors increases the shear strength while increasing height decreases the resistance of the C- shape and increases the L-shaped resistance. The researchers at The University of Belgrade (Pavlović, Gluhovic, & Markovica,2017) [8] tested the shear capacity of X-HVB shear connectors. An experimental study was conducted using precast composite slabs with X-HVB acting as a shear connector, Fig. The tests showed that the specimen with connectors in the forwarding orientation had a higher resistance. The slip between the slab and the steel beam was greater than 6 mm, which is the value required in EC4 to consider the shear connector is ductile.

Fig (2) X-HVB shear connector

The new bonding system developed and patented by (Marimon, Casafont, and Ferrer,2018) [4] called UPC System, consists of producing bands of many small crown-shaped cuttings by punching the steel

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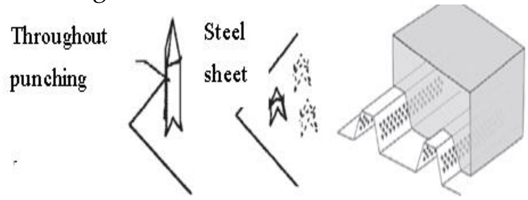

Fig (3) The new bonding system named UPC [4]

sheet before profiling as an alternative to the usual embossing system see Fig. The effectiveness of this invention lies, in the small size of the crowns, many in number, and uniformly distributed so that they confine a concrete mass that increases the bonding and friction between the concrete and the steel sheeting .as a result it prevents the occurrence of slip. An experimental study was conducted by (Galjaard & Walraven, 2001) [6] on different shear

connections under static loads in composite beams in the laboratories of Delft University. These shear connectors are headed studs, oscillating perfobond strips, perfobond strips, waveform strips, and T shear connectors, Fig. The behavior of the oscillating strips is a little disappointing compared to studs, for example. Perfobond strip collapse was sudden after reaching the ultimate load, but it showed better ductility than the Oscillating strip. T- Shear connector had a promising behavior, showed high resistance to shear, and was ductile, the study was conducted according to the EC4

The reference study shows the possibility of having a high shear bonding performance between the concrete slab and steel sheets containing crowns, and this model has been used effectively in slabs for residential buildings. No studies have been conducted on the use of crown technology in residential buildings' composite beams, and herein lies the research problem.

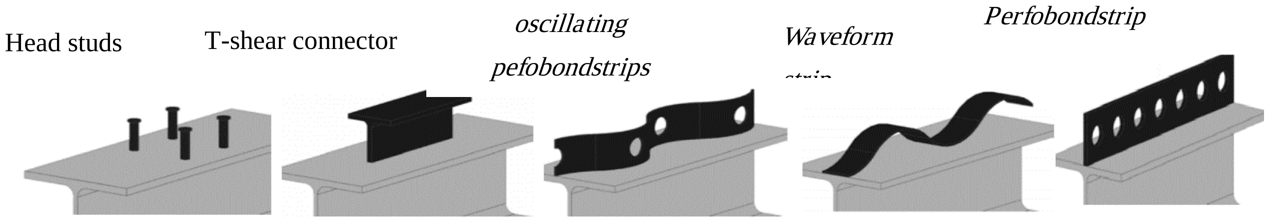

Fig (4) (Galjaard, Walraven, 2001) studied different types of shear connectors [6]

1. Research objective:

The goal of this research is to create a technique of numerous shear connectors that resembles the technique of crowns with superficial shear action. This new method confines a concrete mass, increasing bonding and

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friction between connectors and the concrete slab. As a result, it has high shear resistance and prevents slipping between the concrete slab and the steel beam. To achieve an unwelded model with bolts acting as shear connectors in composite beams under static loads.

2. The finite element model

The finite element model to be built is new in terms of numerical construction because the idea is drawn from a previous study (Ferrer, Marimon, & Casafont, 2018) [4]. The idea is to replace the single shear elements with a shear area created as a result of a large number of contact points. The numerical model for finite elements will be adjusted by building experimental tests for the model in the University of Damascus laboratories. The first stage is to build a numerical model by EC4, and then tests will be built to achieve two goals: calibration of the model, and verification of the obtained variables.

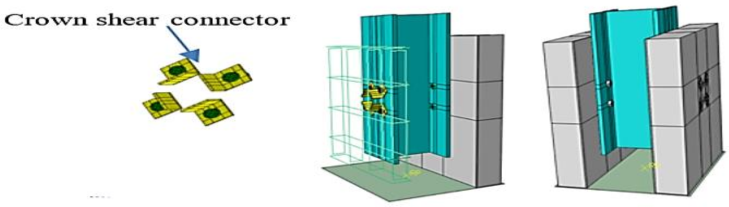

Fig (5) Finite element detai

An accurate finite elements model significantly reduces the number of tests needed to predict the construction behavior of a specific system. Therefore, the Push-Out test required by the European code to test the shear capacity was modeled in Abaqus using the new crown shear connector (four bolted angles together forming a crown shape). To achieve accurate FEA results, all details of the Push-Out test were designed. The FE model consists of eight parts: concrete slab- steel beam - metal angle- bolt – nut - vertical reinforcement bars -horizontal reinforcing bars- rigid base. As shown in Fig

3. Mesh

The Solid element C3d8R was used to divide the concrete slab, steel section, and angles. The truss element T3D2 is used to model the reinforcing bars in the concrete slab, while the solid element C3D4 was used to model the bolts and nuts due to the difficulty of dividing the threads of the bolts and nuts. See Fig **(1**

Abaqus/Explicit was used in the quasi-static analysis by smooth steps to keep inertia to a minimum. The loading consisted of two stages: The first is bolt preload in which displacement-controlled loading is applied on the nuts according to their local axis so that it turns and tightens the bolt.

Tangential displacements were applied on the edges of the nuts (u=3mm) so that it turns clockwise. The bolt’s head was restrained so that tension is done as it happens in push-out tests. The second stage is vertical loading in the steel beam’s longitudinal axis direction. Displacement-controlled loading is used. The loading is applied on the upper surface of the steel beam. Displacement is zero at the onset of loading, and then

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gradually increases according to the smooth step amplitude function. A value of U2=30mm was applied. see Fig

4. Constraints and interaction

The reinforcing bars are inside the concrete slab; therefore, the embedded constraint was used for modeling the contact between the concrete and the reinforcing bars. The reinforcing bars are the embedded regions, the slab is the host, see Fig

A general contact interaction procedure is used for modeling the contact between the concrete and steel angles within the slab. In the normal direction: hard contact, for the tangential direction: penalty, friction coeff =0.45 [9]

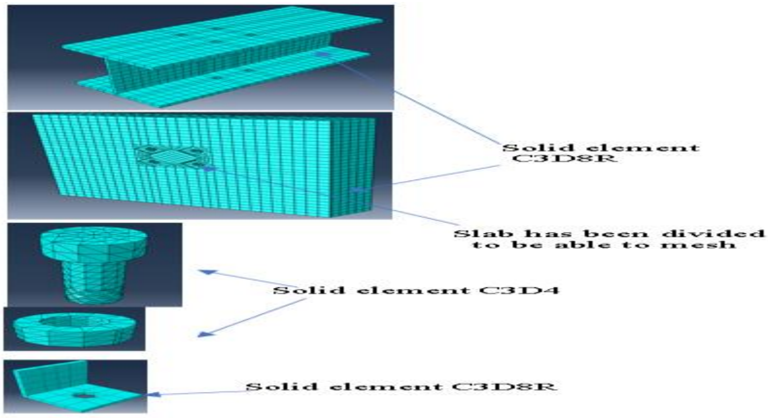

Fig (1) FE model mesh

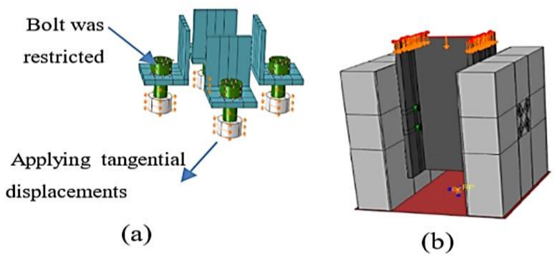

Fig (7) Loading stages:
(a) Bolt preloading, (b) Failure loading

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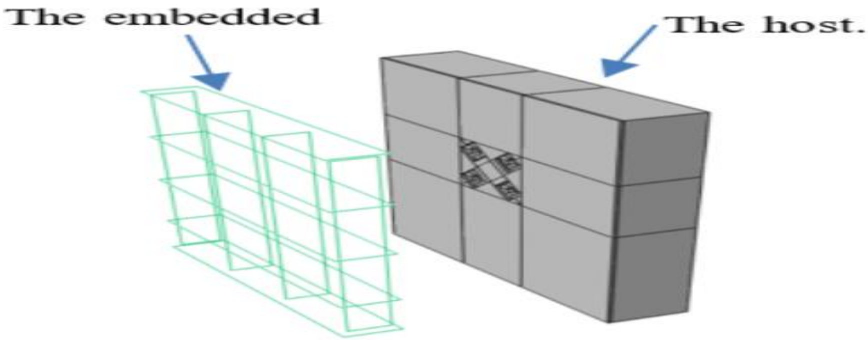

Fig (8) The embedded constraint

The surfaces that are not subject to this connection were excluded, such as the two steel beam surfaces in contact with the slab; the two slab surfaces in contact with the steel beam; the metal angle surfaces in contact with the steel beam flange; the slab surfaces in contact with the rigid base, the top surface of the rigid base. Suitable contact has been applied to each. Surface-to-surface contact interaction was used for modeling the contact surface between the two surfaces of the steel beam flanges and the concrete slab surfaces contacting the steel beam, which are greased before the test, see Fig (a).
Normal direction: hard contact, tangential direction: frictionless.

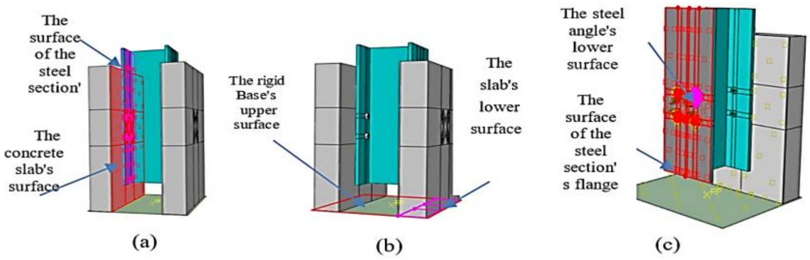

Fig (9) Surface-to-surface contact interaction

Surface-to-surface contact interaction was used to
model the connection between the two surfaces of the steel beam flanges and the angles' bottom surfaces in contact with it, see Fig (c).
Normal direction: hard contact, tangential direction: friction contact.
Friction factor = 0.14 [9][7]
Surface-to-surface contact interaction was used to model the connection between the lower surface of the concrete slab and the rigid base, see Fig (b). Normal direction: hard contact, tangential direction: friction contact, friction coeff =0.6.

5. Material properties

a. Steel

The stress-strain behavior of steel angles,

steel sections and reinforcement is similar. It behaves as a linear elastic material up to the limit of plasticity and then behaves
as plastic material. see Fig.
elasticity modulus= 205 GPa and the density
γ =7850kg/m3.The Poisson ratio υ = 0.3
For angles Fy =375N/mm2
For steel section Fy =235N/mm2
For steel reinforcement Fy =400 N/mm2

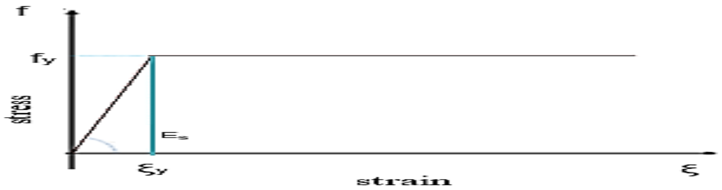

Fig (10) The idealized stress-strain behavior of steel

b. Concrete

Most studies used concrete damaged plasticity (CDP) to model concrete behavior, according to the reference studies. This model considers stiffness and modulus of elasticity degradation caused by tensile and compressive plastic deformations. The relative stress-strain curve of concrete (Pavlović, 2013) [9] is adopted, and the coordinates of the points are obtained from the reference study's data. Dilation angle=36, eccentricity=0.1, Fb0/fc0=1.2, k=0.59, Viscosity Parameter = 0

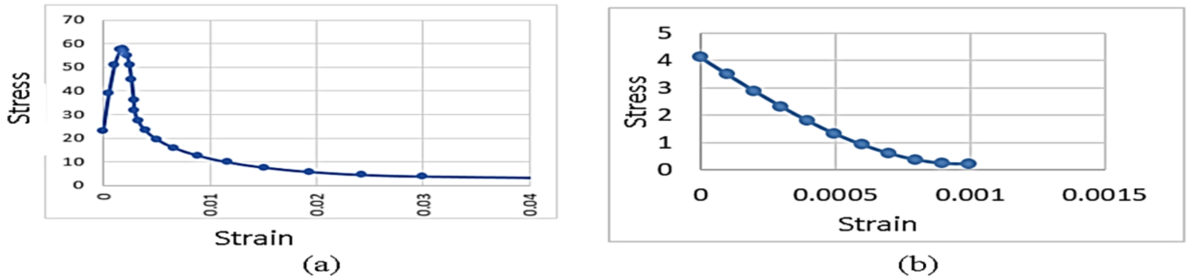

Fig (11) Stress-strain curve of concrete C58 (a) under compression(b) under tensile.

Concrete C38, C48, and C58 were used in this study. The compression behavior of concrete C58 was as shown in **خطأ! لم يتم العثور على مصدر المرجع.**(a)The current study adopts the tensile relative stress-strain curve f concrete from (Pavlović, 2013) [9], and the coordinates of the points are extracted from the data of the reference study. The tensile behavior of concrete C58 of the used grades (C38, C48, and C58) was shown in **خطأ! لم يتم العثور على مصدر المرجع.** (b).

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c. Bolts

The ductile damage material model in Abaqus is based on the reduction of the initial material modulus of elasticity E, depending on an artificial damage variable D,

Ed = (1-D) E. A damage initiation criterion and the damage evolution law define the damage model. The damage variable D=0 at the onset of damage. The onset of damage is defined by the damage initiation criterion and it depends on stress triaxiality. After the damage initiation criterion has been achieved, the damage evolution starts. During damage evolution, the damage variable increases to D=1 which corresponds to the total degradation of the material stiffness. The damage initiation criterion can be defined as a function of plastic displacement or fracture energy.

The progressive shear damage model in Abaqus is again defined by the damage initiation criterion, and damage evolution law. The damage initiation criterion is defined by fracture strain=0.08.

The shear stress ratio=1.732, strain rate=0.1, and material parameter ks=0.2. Displacement-controlled shear damage evolution law was used with exponential softening. Multiplicative degradation was included allowing for interaction with the ductile damage (Abaqus, 2012) [1], displacement at failure=0.3, exponential law parameter=0.7

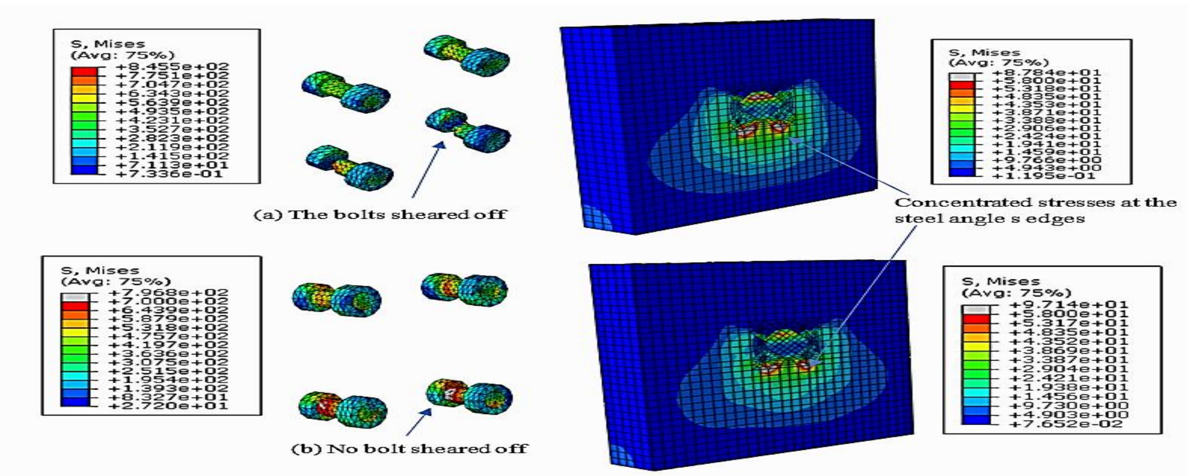

Fig (12) Failure mode :(a)with concrete C58, (b)with concrete C38-C48

6. Discuss the results

The result of using concrete C58 for the slab shows shearing of the bolts with a collapse in concrete at the stress concentration positions at the edges of the angles, see Fig(a). The results of using concrete C48 and C38 show that a failure occurs in concrete at places of concentration stress at the edges of the angles without reaching the stage of Shearing the bolts

The diagrams shown in **خطأ! لم يتم العثور على مصدر المرجع.** demonstrate the relationship between the force pplied on the top of the steel beam and the slip between the slab and the steel beam, for concrete C38, C48, and C58, which enables to extract of shear strength P, P_{uk}, δ_u, δ_{uk} for each of them.

P_u is the shear strength, and P_{uk} is the characteristic resistance $P_{uk}= 0.9 P_u$

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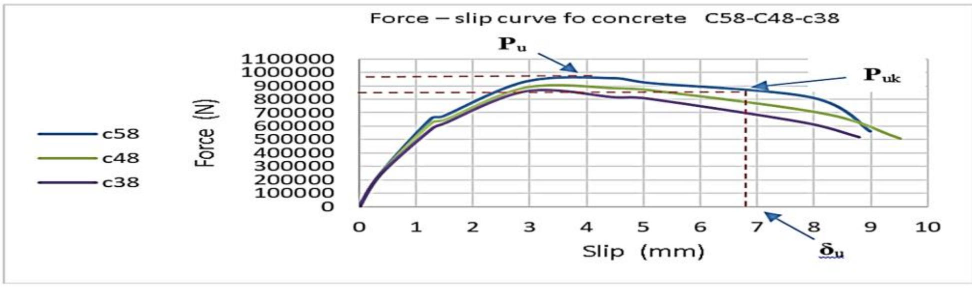

Fig (13) Force–slip curve by using a crown shear connector.

δu the slip capacity of a specimen corresponding to P_{uk}.

δ_{uk} the characteristic slip capacity δuk =0.9 δ_u

For concrete C58: P_u=956.9 Kn, P_{uk}=856 Kn, δ_u=6.9 mm, δ_{uk}=6.21mm >6mm,

As a result, when C58 is used, the crown shear connector is ductile.

For concrete C48: Pu=900kn, Puk=800 Kn, δu=6.33mm, δuk=5.67mm <6mm

For concrete C38: Pu=858kn, Puk=774 Kn, δu=5.9mm, δuk=5.31mm <6mm

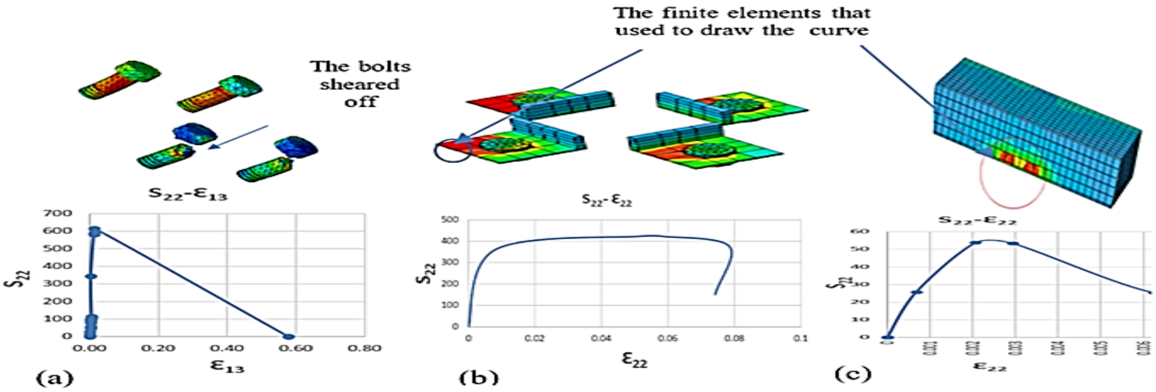

Fig (14) Stress-strain curves: (a) bolt, (b) angle, (c) concrete.

As a result, when C48 and C38 are used, the crown shear connector is not ductile.

The stress-strain curve S_{22}-$Ɛ_{22}$ was obtained by taking elements from the collapsed area in the concrete, as shown in Fig (c).

Furthermore, the elements of the collapsed area of the angle were identified, and the stress-strain curve S_{22}-$Ɛ_{22}$ was determined, as shown in Fig (b).

The elements from a bolt's collapsed area were selected, and the stress-strain curve S_{22}-$Ɛ_{13}$was drawn in the curve shown in Fig (a).

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The force-slip curve resulting from using the new crown-shaped shear connector with C38 concrete was compared against the results of the study (Galjaard & Walraven, 2001) [6] that used the same
resistance C38, dimensions specified in Eurocode EC4 for standard push test, as in Fig (b).The figure shows that the crown shear connector achieved a shear capacity approximately equal to welded studs (there were four welded studs per slab) but less ductility. Also, by comparing the force-slip curve resulting from the use of a crown shear connector with C38 concrete with the results of the
CT sample containing four M24 bolts, two per slab in the research (Pavlović, 2013) [9] as in Fig (a).

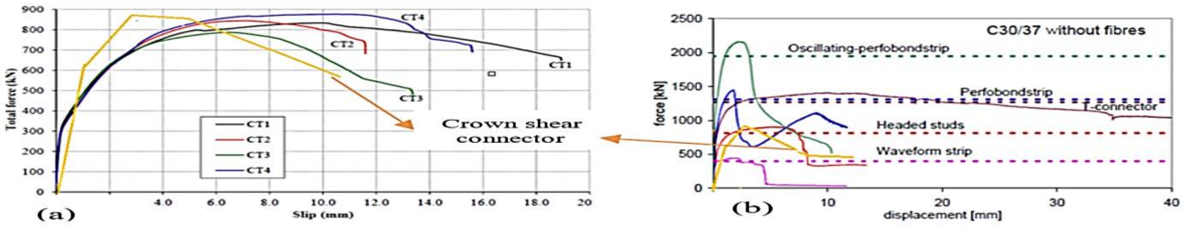

Fig (15) Comparative between the crown shear connector and different shear

It was found that the crown shear connector gave a resistance equal to the resistance given by the CT samples, but it was less ductile.
This article considers only creating the numerical model. The model will be calibrated based on experimental tests that are being built in the laboratories of Damascus University. The aim of this article is not to present consistent results, but rather to show that there is preliminary research that proves possible the investment of surface contact resistance that replaces conventional shear connections.

6. Conclusions and recommendations

The crown shear connector, which was made up of four bolted metal angles, provided a high shear capacity and could be used in place of welded studs. Furthermore, the crown shear connector demonstrated ductility when C58 concrete was used, with a slip greater than 6 mm, which is the minimum required to be considered a ductile shear connectoraccording to the European code EC4.
The failure modes of the model are related to the strength of the concrete used; as the resistance of the concrete increases from C38, C48, to C58, the failure mode of the model changes from concrete failure only to concrete failure accompanied by bolt shearing. The shear capacity of the crown shear connector increased when C58 was used, and this relationship between shear capacity and concrete strength (C38, C48, and C58 were used) can be seen. Additionally, given that the ductility of the crown shear connector increased when C58 was used, the strength of the concrete used is related to the ductility of the connector as well.

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