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Web Shear Strengthening Technique of Deep Precast Prestressed Hollow Core Slabs under Truck Loads

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Abstract

Precast prestressed Hollow Core Slabs (HCS), are one of the famous and widely used slabs for concrete structures all over the world and widely implemented in the Middle East. HCS are used in industrial, commercial, residential buildings, as well as, in the parking structures. This paper succeeded to present new special details for deep HCS to enhance and strengthen the web shear strength capacity of HCS 400 and 500 mm depths respectively at the open parking area. This is subjected to heavy truck wheel loads so as to achieve the LRFD Code's requirements. However, it is noticed many web shear cracks of HCS are used at parking area at many projects in Gulf Region. On the other hand, ACI318-14 permits no shear reinforcement in prestressed HCS thickness of less than 12.5 in (320 mm). The paper presents experimental tests program, to verify the numerical finite element of deep HCS under maximum design uniform loads, in addition to the new strengthening techniques. New strengthening techniques succeed to enhance the web shear capacity by significant percentage, due to the new details for HCS 400 by 68% up to 256% increasing of the web shear capacity compared to the ordinary HCS section. Also, HCS 500 shear capacity is enhanced with different percentages of strengthening techniques by 55%, up to 197% based on the different cases of strengthening. Furthermore enhancing deep HCS shear performance; the new techniques have an advantage of an easy execution at the site; casting with structural topping, otherwise the preparation can be done in precast factory before site handover, which saves time and cost compared to the others traditional strengthening techniques.

Keywords

Hollow Core Slabs, Shear Stress, Prestressed Slabs, Shear Strength

1. Introduction

Since the early eighties of twenty century, the slab cross-sections with non-circular voids have become commonly used gradually; as an easy and quick construction technique. Precast slabs become widely used end of twenty century to get quick construction with high quality. These deeper precast prestressed hollow slab units are increasingly used in the industrial buildings and office buildings where large spans of open parking spaces on ground floors are provided with columns spacing modules from 10 m to 17 m. As a consequence the deeper hollow core slabs are designed to resist higher loads and to support the longer span with minimum own weight of slabs. A hollow core slab is a precast, prestressing concrete member with continuous voids being provided to reduce weight and cost. These slabs which are made of high-strength concrete are prefabricated concrete members with large hollow proportions. In practice, they are interconnected after assembling them through a joint grouting compound. On the contrary to the conventional concrete members, the prestressed hollow-core concrete slabs have many advantages, such as saving the material, speed of installation, lower building costs, moreover ensuring consistent quality levels, good fire resistance, and sound insulation properties. This is addition to its capability of spanning long distances with relative small depths. Hollow core slabs can make use of prestressing strands, which allows the slabs; their depths approximating between 400 and 500 mm, in order to span 14 up to 18 meters in standard widths of 900 mm and 1200 mm which are more common in the market [1] [2].

Prestressed hollow core units have longitudinal cores of which the main purpose is to reduce the weight of the floor. They are mainly used in buildings with large spans, such as office buildings, hospitals, schools, shopping areas, industrial buildings, etc. Another frequent application is for apartment and housing buildings because of the favorable cost rate and the fast erection. They are built of either reinforced or prestressed concrete.

The elements are available in different depths to satisfy the various performance requirements in respect of span and loading. Typical cross-sections are shown in **Figure 1**. The percentage void (volume of voids to total volume of solid slab of equal depth) for HCS is approximating between 30% and 50%.

Prestressed hollow core units are normally 1200 mm wide and reaching to 20 m long. The actual unit's width is usually 3 to 6 mm approximating, which is less than the nominal size allowed for constructional tolerances, which prevents overrunning of the floor layout due to cumulative loads over the width. The edges of the units are profiled to ensure an adequate vertical shear transfer across the grouted joint located among adjacent units.

Prestressed hollow core units are manufactured using either long line extrusion or slip form processes. The steel or concrete beds are usually with 1200 mm width and 80 to 150 m length. The degree of prestress, strand pattern and depth of units are the main design parameters. In some countries, an alternative process, called "wet-casting", is also used. The latter elements are characterized

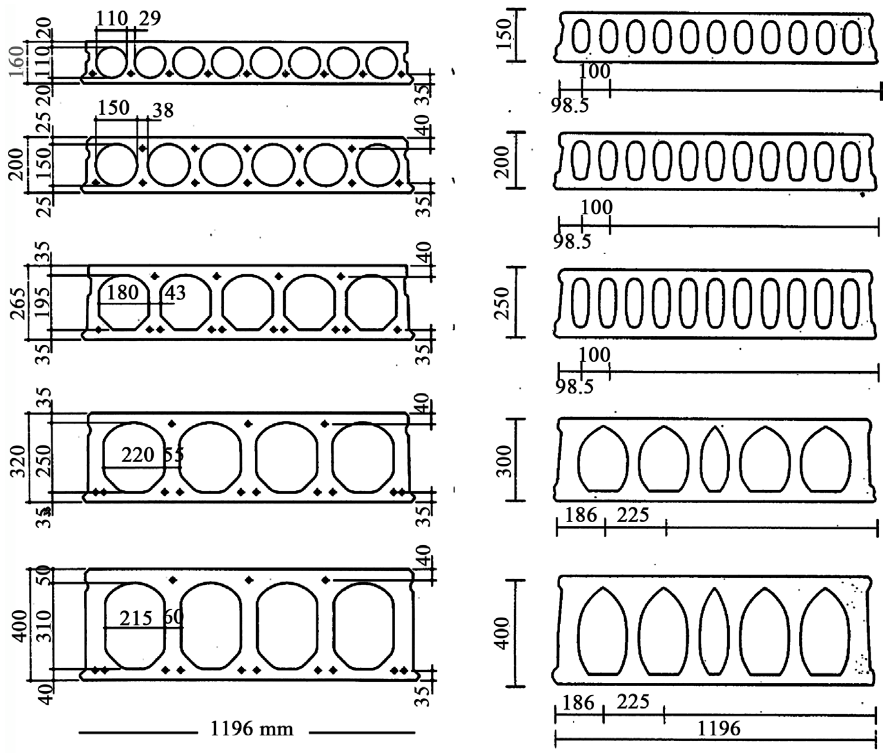


Figure 1. Typical cross-sections of prestressed hollow-core elements.

by large square openings [3] [4] [5].

After hardening, the elements are cut into the specified lengths using a circular saw. A rectangle's end is standard, but it is skew or cranked ends, which are necessary in a non-rectangular floor plan, that may be specified.

It is mostly obvious, that HCS 400 and 500 mm thickness are used in heavy traffic loads, especially in the parking areas located at buildings like malls, and commercial, residential, and university buildings. There are many of deep HCS suffering shear cracks in most of the areas being exposed to heavy truck loads; especially for HCS's with 400 and 500 mm thickness.

One example for this project is the parking area in Girls Campus in King Saud University (GCKSU), located in Riyadh, KSA. This parking area is located in the main front of Administration Building with an overall opened parking area of about 15,000 m^2 being used for the buses ,which is also used wherever carrying out the University's maintenance works. Figure 2 shows the statical system of one way HCS 400 mm with span 14 m. HCS is simply supported on two precast non-prestressed beams with a span about 9.8m of each beam. The web shear cracks are recurrent at many areas of the parking area that are subject to heavy trucks as it monitored and shown in Figure 3. After checking the design of this HCS slabs, it was ensured as being completely safe and it's sufficient structurally as per ACI-14 and PCI-2007 [6] [7] under a live load equal 5 kN/m^2 as per the original design criteria of project. However, the web shear cracks were noted and monitored in most of the areas exposed to heavy truck loads. Web

Figure 2. General view of HCS 400 mm roof slab of the parking area, GCKSU.

Figure 3. Web shear cracks of HCS 400 mm.

shear failure is caused by a diagonal crack at the web of HCS appeared in the first quarter of HCS span between the concentrated load of truck wheel loads and beam support; as shown in **Figure 4**. This type of shear failure usually occurs when a maximum principal stress results from combined effects of shear and bending exceeding the tensile strength of concrete [3] (S. Pereira, 2013). This type of failure is classified as a very dangerous type where no cracks cloud is observed or noticed at the failure section; just the resultant shear stress exceeds the tensile strength of concrete. The suddenly appearing diagonal cracks which may lead to sudden total collapse of HCS. The web shear failure is more likely to occur at the members with a high flexural resistance capacity, *i.e.* high prestressed deep HCS 400 and 500 mm depth, respectively, when exposed to concentrated load close to the support.

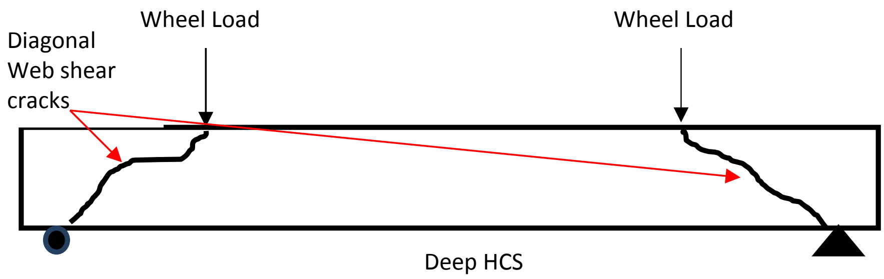


Figure 4. Sketch of web shear cracks in deep HCS

Insufficient design web shear is noticed at many of existing projects in KSA, at which deep HCS was used, with a thickness of 400 and 500 mm; under the same circumstances of loadings and structure system. Most of precast factory molds are produced at ELMATIC precast technology stander [8], which is widely used in Middle East and Gulf region.

The geometric cross section of this type of European Factory of ELEMATIC precast factory technology supplier, exemplified at **Table 1** with all natural properties and reinforced details, as per supplier's stander.

2. Shear Stress Design of Deep HCS

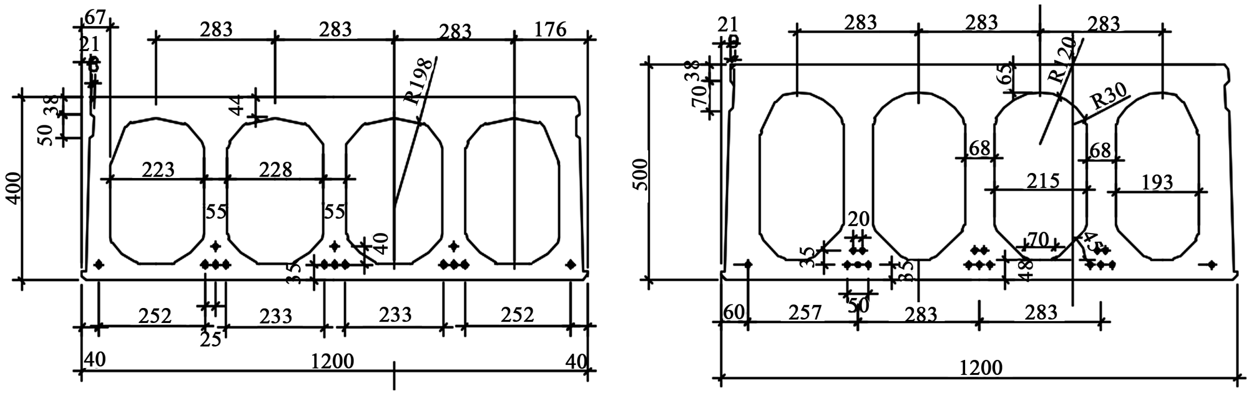
In the American Concrete Institute's ACI 318-14 [6]; two different types of shear cracking is defined for the prestressed concrete members. The first is the web-shear cracking, and the second is the flexure-shear cracking. The flexure-shear cracking-strength expression was derived by adding the incremental shear force (the first term of ACI 318-14 Eq. (22.5.8.3.1a)) as shown in **Figure 5**. For the web shear cracking strength, the equation was derived based on a simplification of the classical principal stress formula where the maximum principal tensile stress is equal to the tensile strength of the concrete. Details of the derivations of the ACI 318-14 predicted that shear strength equations can be found in ACI 318-63 [9].

In ACI318-14 Code requirements for structural concrete, and Commentary (ACI 318R-14) are used for both hollow-core slabs and the typical prestressed concrete flexural members. ACI 318-14 (Section 7.6.3.1) requires shear reinforcement for hollow-core units with a total untopped depth greater than 12.5 in. (320 mm), where the factored shear force at section V_u exceeds $0.5\phi V_{cw}$ (where V_{cw} is nominal shear strength provided by concrete when diagonal cracking is resulted from a high principal tensile stress in web; ϕ is the strength-reduction factor and equals 0.75).

The depth and shear demand limitations were defined on the research results that concluded that prestressed concrete hollow-core slabs with a depth greater than 12.5 in. Generally showed web-shear strength in end regions is much less than the one predicted by (ACI 318-14), V_{cw} equation (ACI-22.5.8.3.2).

In ACI 318-14, the nominal shear strength is defined by the concrete V_c for hollow-core slabs with a total untopped depth not greater than 12.5 in. (320 mm) shall be the less than of the flexure shear cracking strength V_{ci} and the

Table 1. ELEMATIC Hollow core reinforced and geometry properties.



	400 mm Hollow Core Slab			500 mm Hollow Core Slab	
400 mm Hollow Core Slab	Precast slab weight	4.15 kN/m²	500 mm Hollow Core Slab	Precast slab weight	6.0 kN/m²
	Area of section	0.2074 m²		Area of section	0.304 m²
Bottom strands (full Bonded)		14T12.7 mm	Bottom strands (full Bonded)		17T12.7 mm
Top strands		N.A.	Top strands		N.A.
Prestressing details for strands	12.7 mm (Bottom)	9.53 mm (Bottom)	Prestressing details for strands	12.7 mm (Bottom)	9.53 mm (Bottom)
Pulling force (Ibs)	24,850 Ibs	13,850 Ibs	Pulling force (Ibs)	24,850 Ibs	13,850 Ibs
Elongation (100%) (mm)	840	840	Elongation (100%) (mm)	840	840
Elongation (10%) (mm)	84	84	Elongation (10%) (mm)	84	84

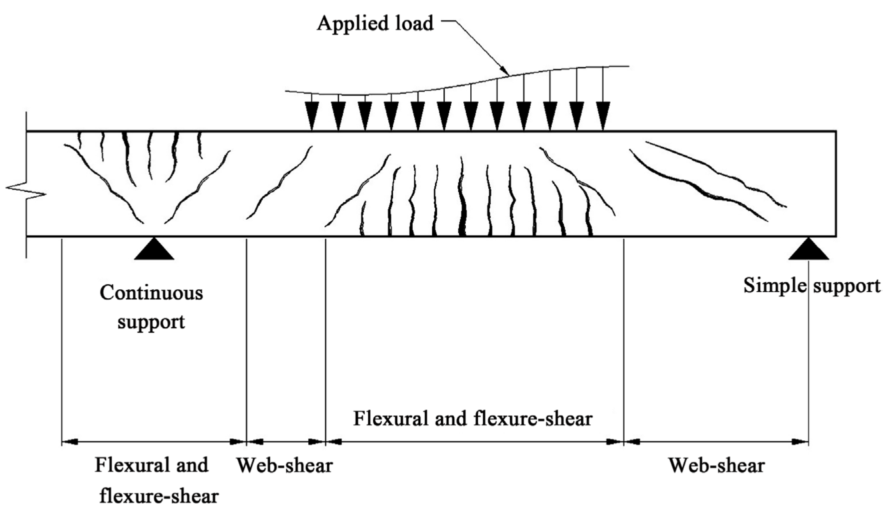


Figure 5. Types shear cracks for prestressed concrete member [6].

web-shear cracking strength V_{cw}, where V_{ci} and V_{cw} are expressed in the following equations:

The flexure shear strength V_{ci} shall be greater in terms of the following two equations:

$$V_{ci} = 0.05\lambda\sqrt{f_c'}b_w d_p + V_d + \frac{V_i M_{cre}}{M_{\max}} \quad \text{(ACI-22.5.8.3.1a)} \tag{1}$$

$$V_{ci} = 0.14\lambda\sqrt{f_c'}b_w d \quad \text{(ACI-22.5.8.3.1b)} \tag{2}$$

where d_p needs not to be taken less than 0.8 h, the value of $M_{\max}$ and V_i shall be calculated from the load combinations causing maximum factored moment to occur at section is considered, and M_{cre} (moment causing flexural cracking at section due to externally applied loads). It shall be calculated by:

$$M_{cre} = \left(\frac{I}{y_t}\right)\left(0.5\lambda\sqrt{f_c'} + f_{pe} - f_d\right) \quad \text{(ACI-22.5.8.3.1c)} \tag{3}$$

The web shear strength Vcw shall be calculated by

$$V_{cw} = \left(0.29\lambda\sqrt{f_c'} + 0.3 f_{pc}\right)b_w d_p + V_p \quad \text{(ACI-22.5.8.3.2)} \tag{4}$$

where d_p needs not to be taken less than 0.8 h, f_c' is specified compressive strength of concrete, f_{pc} is compressive strength, I is concrete at centroid of cross section resisting external applied loads after allowing prestress losses, and V_p is the vertical component of the effective prestress.

3. Experimental Program Setup

In order to verify the numerical model; an experimental program is carried at for two HCS's: one is 400 mm and the other one is 500 mm thickness. All HCS samples are delivered from the same precast factory located in KSA, to ensure the same production quality, treatment, and casting circumstances. The design was developed as per PCI2007 Code. The experimental work was done by ACES (Arab Company for Laboratories and Soil); it is specialized certified laboratory in KSA and AUE. The samples were tested; first sample is HCS400 with a 14 m span, and the second is HCS 500 with a 17.5 m span. The geometry and design data are summarized as listed in **Table 1**. Both samples of HCS are with 1200 mm width, as per ELEMATIC precast technology [8] Stander of machines production.

The two samples are loaded as simply supported one way slab under full design capacity loading. Deflection was monitored at mid span using LVDT instruments. The two samples have been checked through visual inspection before selecting them from the storage area of the precast factory. Two HCS samples are pre-tensioned with seven-wire low relaxation strands (12.7 mm in nominal diameter). HCS400 and HCS500 has 14 and 17 strands (12.7 mm strands), respectively without top strands. The both strands are placed with a 30 mm bottom cover. Both samples are pre-tensioned to 75% of an ultimate strength fpu = 1900 MPa, before the concrete was cast using dry mix extrusion procedures. The applied prestressing force is transferred to the concrete 20 hours after casting. The details of the slabs cross-sections and their properties are shown at **Table 1**.

Figure 6 shows the static system of test setup of HCS loading system. The two Hollow Core Slabs are simply supported under uniform loads; gradual loading

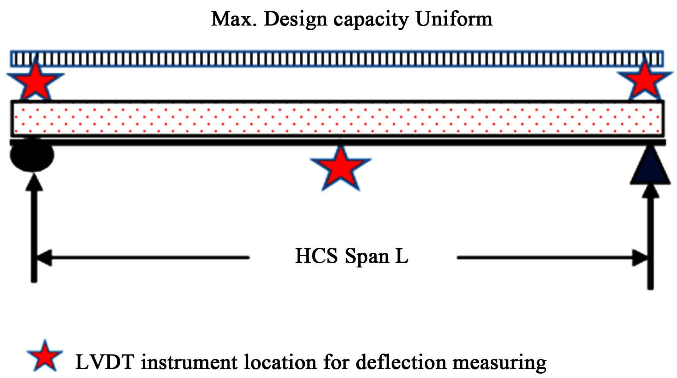


Figure 6. Experimental test setup of HCS loading and statical system.

to the maximum design capacity loads, three LVDT are fixed; on two supporting points, to measure any supporting rotation during the loading stages and the third one is fixed at the mid span of HCS, to measure the deflection value.

Figure 7 and Figure 8 show 400 and 500 mm HCS respectively at an initial stage of the loading using reinforcement concrete segments to load each piece to the maximum design loading. As shown at the both Figure 7 and Figure 8, the experimental loading test was conducted the reinforcement concrete mat foundation with rigid stiffness, so as to avoid any rotation or differential settlement that may occur between two supporting points. Raft testing table was designed to carry out the expected stress safely during the loading test.

Two of LVDT instruments are fixed at the supporting points as shown at Figure 9; to monitor any supporting rotation, where it is not allowed for any rotation of HCS at the supporting points. Consequently, the bearing length was 300 mmm, which is too much value to avoid any chance of HCS rotation at the supporting points while conducting the loading tests. The third one was fixed at the mid span of HCS sample, to measure the maximum deflection value during loading test and after 24 hours of maximum loading value.

4. Verification of Finite Element Modeling

In order to verify the finite element modeling of HCS under different loading case and the new techniques which will present at the following sections in this research to enhance and strengthen the web shear capacity of deep hollow core sections with 400 and 500 mm depth. The paper presents three dimensional finite element modeling of the two HCS, which is experimented and loaded up to the maximum design capacity sections. The finite element modeling of HCS is done through one of the special and well-known software; which is Concise Beam ver.4.7 [9]. Concise software is an easy to use program for the design of precast concrete beams and slabs. Concise software can perform a load analysis and design checks in accordance with the latest edition of ACI 318 code parameters. HCS can be conventionally reinforced, partial or full pretension. It produces a model of any cross-sectional shape and can allow the cross-section to vary prismatically (step-wise) over the length of the HCS. A graphical editor al-

Figure 7. General view of experimental setup of HCS400.

Figure 8. Side view of experimental table of test setup of HCS.

Figure 9. Test loading with LVDT tools at support, and mid span, respectively to monitor the deflection value.

lows the user to define any cross-section, including voids with any geometric shape.

Figure 10 presents three dimensional finite element model of HCS400 by Concise software (ver.4.47), HCS which is simulated as prestressed slab, high strength concrete with 40 Mpa, is used geometric with the same geometric properties as it is mentioned above in Table 1; to be fully simulated with experimented samples. Print screen was taken from the software to present the geometry and strands reinforcement distribution as shown in Figure 11.

The verification of shear strength capacity of HCS 400 under the design uniform loads is compared and verified with the experimental test measurements by ACES laboratory in Figure 12; which it seems fully matching with Numerical fi-

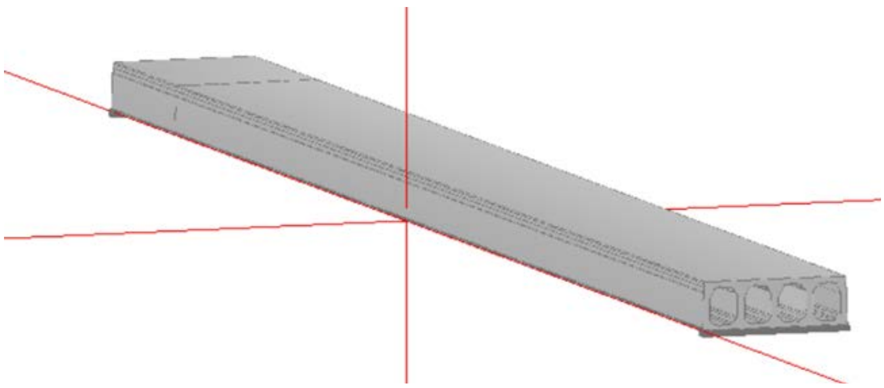


Figure 10. Finite element modeling of HCS 400 mm by Concise.4.47.

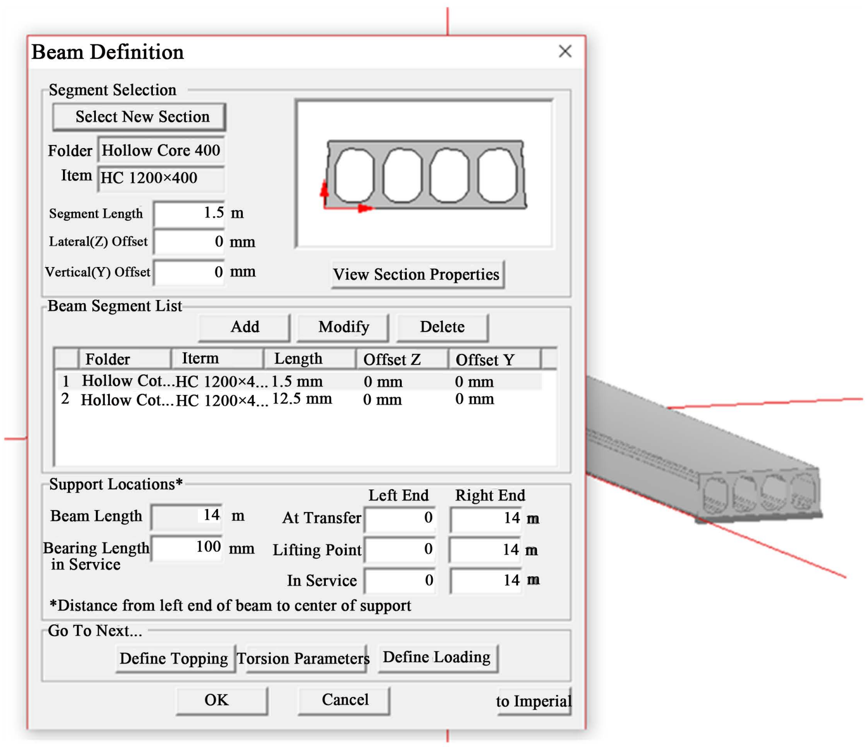


Figure 11. Print screen of concise 4.47 input for HCS 400 geometry and reinforcement.

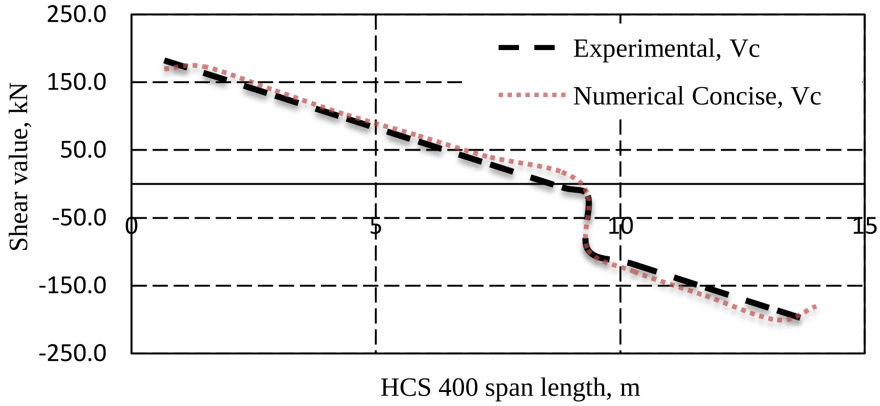


Figure 12. Verification of numerical concise results of shear strength capacity for HCS400 versus to experimental measurement.

nite element modeling results (Concise 4.47) with a maximum error less than 5%.

In finite element modeling, the simulation of loading is adapted to be matching with the experimental test loading pattern, where in experimental loading reinforced concrete block is used away from the centerline of mid span where LVDT is erected for measurements as shown in the above figures; which give an explanation of the shear force diagram is shifted from the mid span for about one meter.

5. New Techniques of Web Shear Strengthening

As per LRFD Code [10]; in the longitudinal direction, the design truck has three axes. The first axe has 8 kips loading, and the second and third axes have 32 kips loadings of each. The spacing between the first and second axles is 14 feet, but the spacing between the second and third axles varies between 14 and 30 feet. The axes spacing is selected so as the maximum effect to be achieved. The minimum 14 feet axes spacing usually controls. However, a situation in which axe spacing is greater than 14 feet may control, is used for a continuous short-span bridge in which the maximum negative moment at the pier is being computed, while the second and third axes are positioned in different spans. The design truck is illustrated in **Figure 13**.

Due to the shortage of web shear capacity of 400 mm depth HCS 400 is used at most of the parking areas under the truck wheel loads, as per the standard LRFD 2015 stating that the maximum wheel loads 32 Kips must be taken (42.34 kN). The numerical nonlinear analysis of 400 mm depth HCS proved the insufficiency of the web shear strength at all opened parking areas wherein there is a high possibility of being exposed to heavy truck wheel loads, so as to be matching with LRFD2015 [11] requirements.

Shear resistance capacity (V_c) of Numerical analysis of HCS400 with simple supporting 14 m span is presented on **Figure 14**; as showing a print screen from Concise 4.47 versus to factored applied shear value (V_f) under critical loading

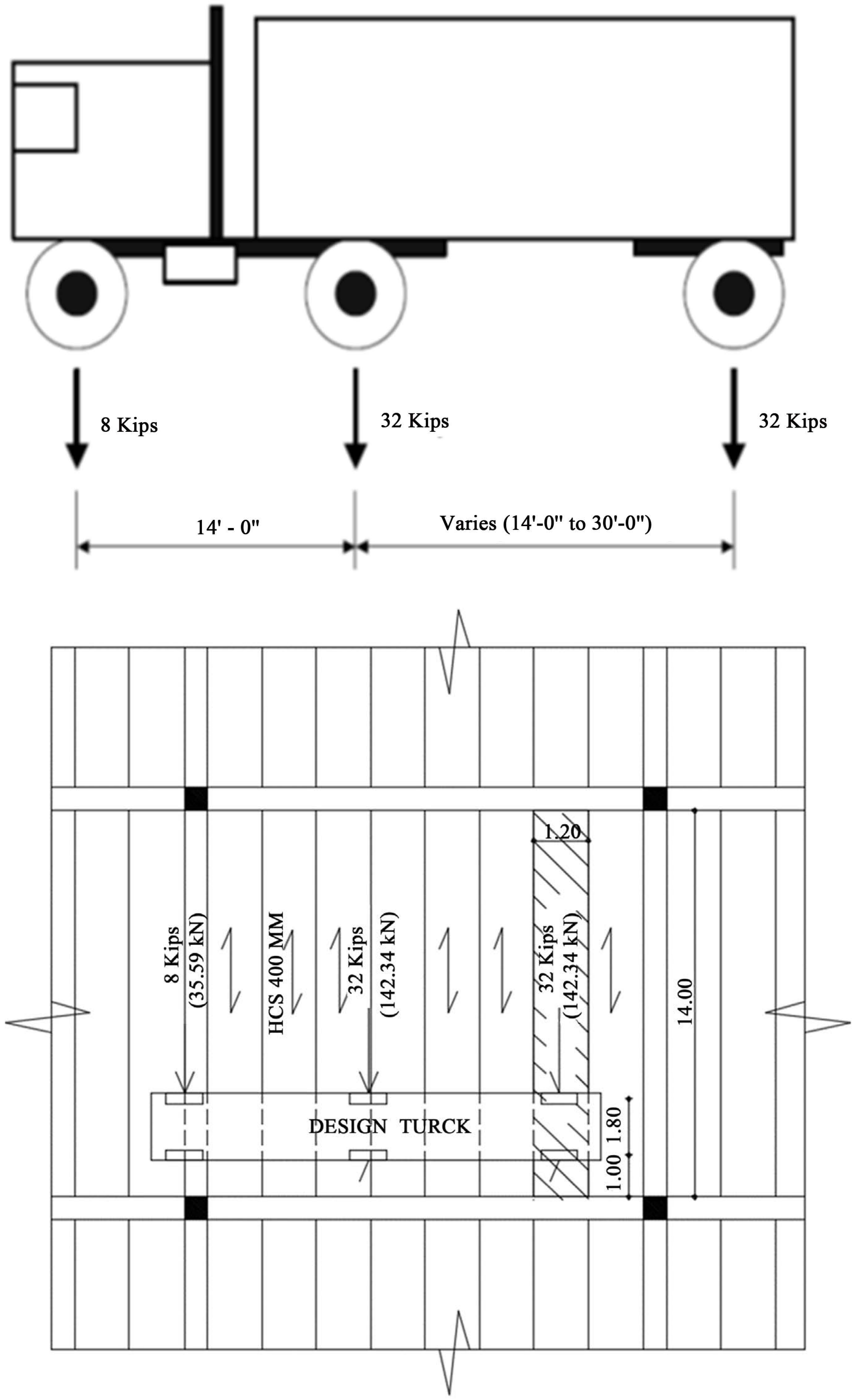


Figure 13. Critical design wheel truck loads as per LRFD.

case of maximum wheel loads of truck as defined at LRFD 2015. The section capacity is unsafe under such truck wheel loads as shown in Figure 14. This inadequacy of shear capacity clarified the web shear cracks that are appeared and shown at the above photos in Figure 3.

The shear strength shortage is cleared when the wheel truck loads are affected

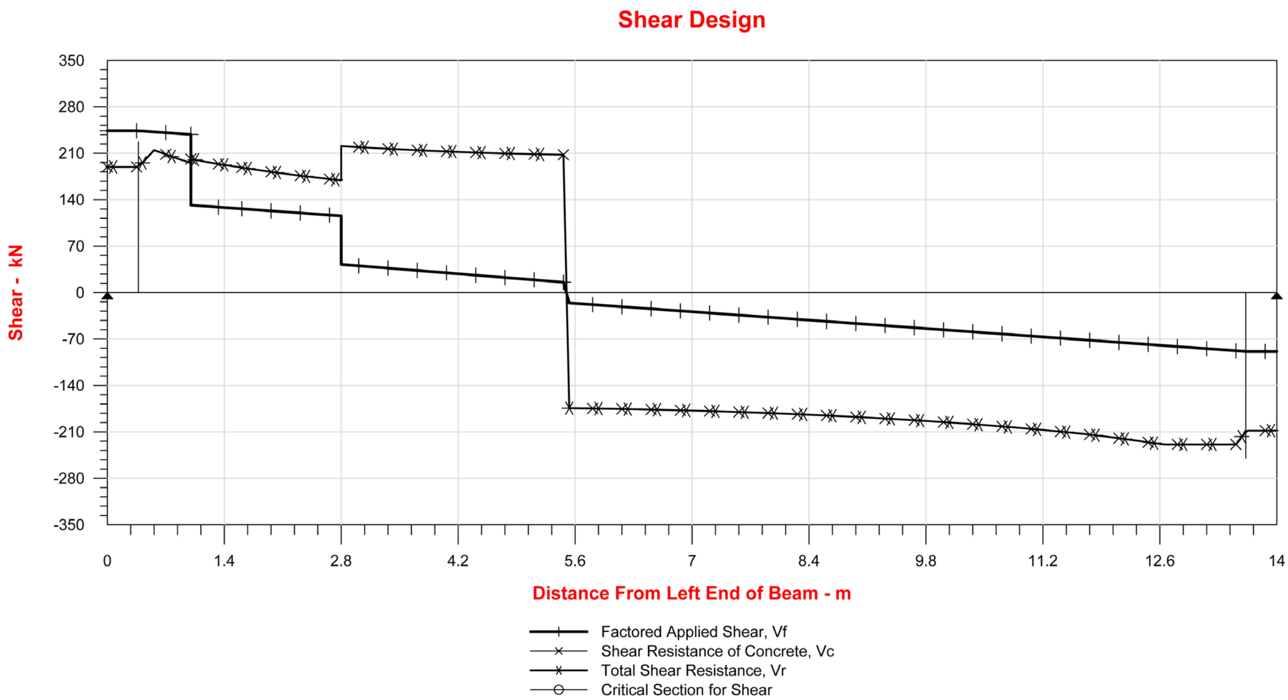


Figure 14. Shear resistance capacity (V_C) of HCS 400 versus to factored applied shear (V_f) under truck loads.

by the heavy wheel loads on one HCS as shown in **Figure 13**; it is obviously, at most of open parking areas in Middle East Region that are exposed to heavy truck loads are experiencing for this problem. It was realized that web shear cracks and failure are experienced at this type of projects.

The paper succeeded to present new strengthening proposal to enhance the web shear strength capacity by increasing the shear web area of HCS, especially for the deep HCS, as the shortage of its shear capacity is obviously shown at the numerical analysis.

In this part, the paper innovates special steel details in respect of cast in place concrete with the structural topping part above the HCS, to enhance the shear web strength by increasing the shear web resistance area. The steel hook inserting at the voids of HCS is placed for the first 1.5 from each edge side of HCS where the maximum shear section, due to the critical truck wheel load as shown in **Figure 13**. **Figure 14** presents all possibilities, of filling and strengthening of the HCS voids for the deep sections: 400 or 500 where both of them in ELEMATIC standard sections have four voids.

Figure 14 is taken as a print screen of the shear value diagram of HCS 400 with 14 m span exposed to concentrated wheel load value of truck as per the LRFD Code, which is presented in **Figure 13**. Green curve of the shear diagram presents (V_c) the HCS Section capacity, and the red curve is factored shear diagram value (V_f); Its cleared the HCS section is unsafe section where the shear capacity of section is inadequate to resist the applied shear force value, due to wheel load value.

The idea of new proposed techniques to enhance and strength the shear capacity of deep HCS 400 and 500 mm depend on increasing the effective shear resistance area at the first 1.5 m from the edges of HCS (at maximum shear sections), by chipping the voids of HCS between the webs to avoid any cutting for imbedded strands at the web sections and adding steel hooks and bottom steel bars at the voids. Steel hooks will be tied with the steel mesh of structural topping, as shown in Figure 15. In Figure 15, the paper presents all available trials to fill one to four voids of ELMATIC Section standard HCS400 and 500.

Loaded sample is tested with the new strengthening techniques as shown in Figure 16. The two outer voids are filled with reinforcement concrete and loaded by concentrated load, which is equal to wheel load truck up to the failure

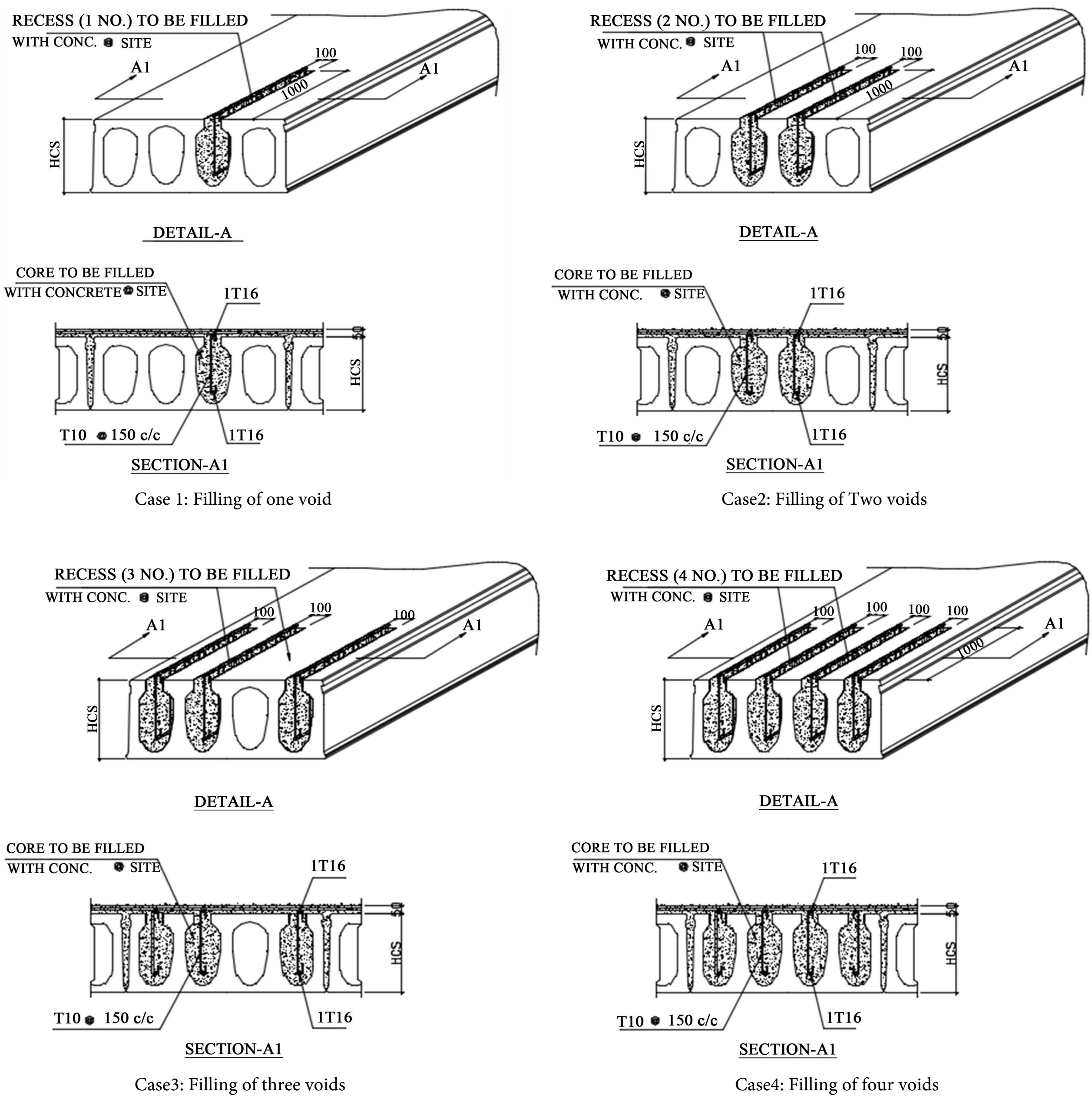


Figure 15. New strengthening techniques of enhancing and strengthening shear capacity.

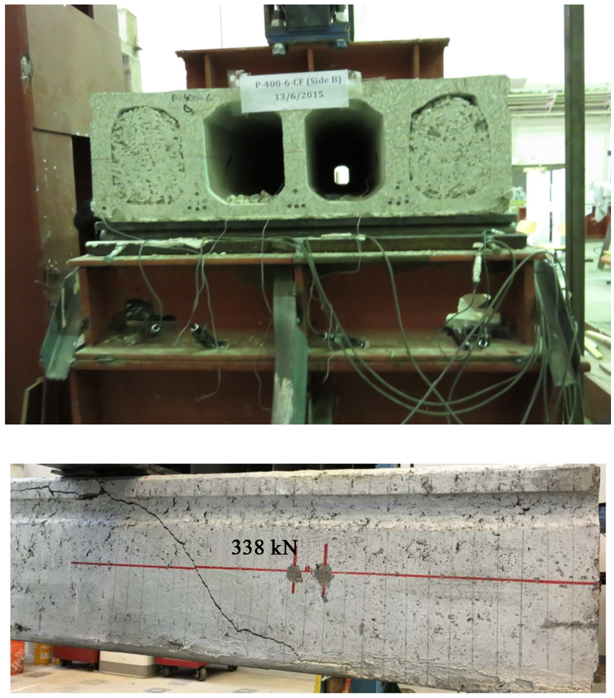


Figure 16. Experimental test web shear failure load of HCS 400mm strengthened for two voids.

point. In the same Figure, the shear failure occurs as expected at the critical section of shear value being about 1.5 m of HCS edge at the shear force "338 KN" (ordinary shear value without strengthening is 175 kN), With a high shear force capacity compared to ordinary HCS Section without strengthening.

In **Figure 17** and **Figure 18**, the full shear force diagrams of 400 and 500 mm HCS depth to percent the shear force diagram for ordinary HCS without any strengthening, compared to the four cases of the strengthening, which is proposed in **Figure 15**.

It is obvious in **Figure 17**, that the strengthened HCS400 has significant improvement of the shear capacity (V_c) with promising values. The web shear capacity enhanced by significant percentage due to the new details of filling one up to four voids for 1.5 m length for HCS from 68%, 134%, 199%, and 256% increasing of web shear capacity of 400 mm HCS compared to the ordinary HCS without filling of slab voids; which is unsafe section under wheel truck loads (V_f).

Also, by the same trend the shear capacity of HCS500 is improved with different percentage of four cases of strengthening techniques, which are 55%, 111%, 151%, and 197% for one void filling up to four filling voids, respectively, as shown in **Figure 18**.

6. Conclusions

The paper presents one of the recurrent construction problems and defects which are experienced at the open parking areas existing at the commercial

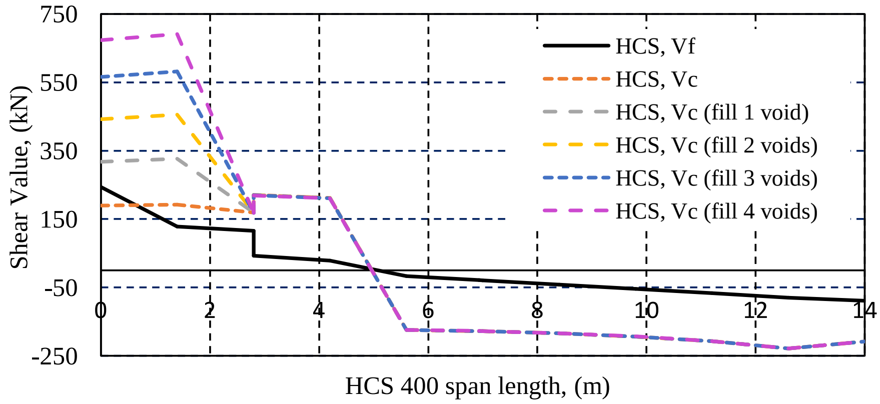


Figure 17. Numerical shear capacity of HCS400 with new strengthening techniques.

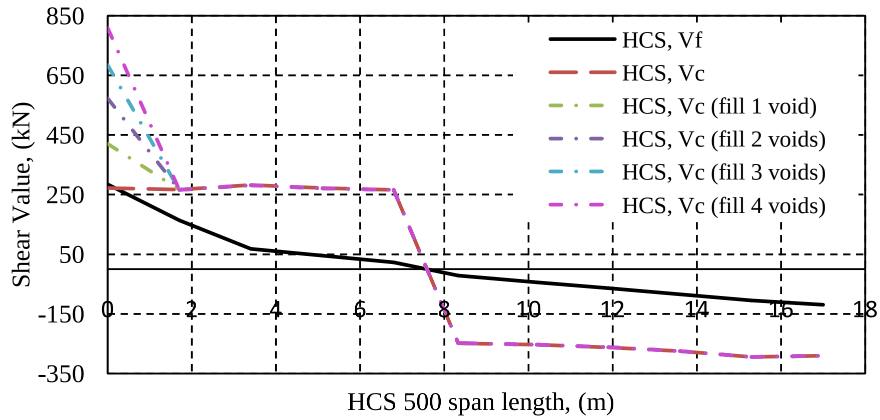


Figure 18. Numerical shear capacity of HCS500 with new strengthening techniques.

buildings and universities. The HCS is widely commercially used in Middle East Region during the last two decays in accordance with ELEMATIC factories standards in respect of deep HCS sections 400 and 500 mm. Most of the defects are resulted from shortage of shear capacity of the deep section which leads to web shear cracks and failure at many projects, as exemplified at the surveying part of this paper.

The paper succeeded to present numerical three dimensional finite elements of prestressed Hollow Core Slab, using one of the well-known and specialized software worldwide called "Concise" (Ver.4.47) which has been verified through experimental test results for verification and confirmation of high accuracy in respect of numerical modeling and simulation of loads. On other hand, the paper presented new techniques to enhance and strengthen the shear capacity of deep HCS "400 and 500 mm" that are normally used for long spans, approximating between 14 to 17 m, respectively; under heavy Truck wheel loads, to achieve the LRFD Design Requirements.

The idea of new strengthening techniques that is presented also was verified with experimental tests results and verified through the numerical results. The new techniques is achieved the goal of strengthening and enhancing of the web shear failure of deep HCS sections at the least possible cost and easy manner of the new long parking spans, or repairing and strengthening of the existing cases, without removing or changing the structural system of parking.

As concluded at the results the new technique succeeded to increase the shear capacity of HCS400, with a significant improvement of the shear capacity (V_c), with promising values. The web shear capacity was enhanced by a significant percentage, due to the new details of filling one up to four voids for 1.5 m length for HCS by 68%, 134%, 199%, and 256%, increasing of the web shear capacity of HCS400 compared to the ordinary HCS without filling the slab voids; which was unsafe section under wheel truck loads (V_f).

Also, the same trend is apparent with the shear capacity of HCS500 which was enhanced and improved with different percentages of four cases of strengthening techniques, 55%, 111%, 151%, and 197% for one void filling up to four filling voids, respectively.

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