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Use of Empirical Shear Connectors in Composite Steel-Concrete Floor Systems

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Abstract– In Honduras, several empirical systems are used as shear connectors for composite steel–concrete floor slabs, such as welded steel bars and U-shaped channels. However, the widespread use of these solutions represents a technical challenge, as their structural performance is not always consistent with established design standards. This study experimentally evaluates the structural behavior of different shear connectors, including both empirical and manufacturer-certified systems, following the provisions of Eurocode 4 and using the push-out test to assess shear resistance, slip stiffness, ductility, and failure mechanisms. Five connector types were analyzed: Hilti X-HVB 95 connectors and Nelson studs as commercial systems, and U-shaped sections, welded steel bars, and welded Nelson studs with E-7018 electrodes as empirical alternatives, testing a total of 15 composite specimens with three specimens per connector type. Results indicate that the highest shear resistance was achieved by the U-shaped connector (462.61 kN) and the Hilti X-HVB 95 (455.85 kN), while the lowest values corresponded to the welded steel bar connector (144.92 kN) and the welded Nelson connector (177.26 kN). In terms of slip stiffness, Nelson (36.59 kN/mm) and E-7018 welded Nelson (35.45 kN/mm) connectors exhibited the highest values, whereas the welded steel bar (10.96 kN/mm) and U-shaped connector (13.13 kN/mm) showed the lowest. These results demonstrate that both empirical and commercial connectors can achieve adequate performance to ensure composite action in floor systems. The comparative analysis supports the technical viability of selected empirical connectors and highlights their practical advantages, including material availability, ease of fabrication, and cost-effectiveness, which favor their continued application in local construction practices.

Keywords-- Empirical connectors, Load-bearing capacity, Push-out test.

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Abstract* – In Honduras, several empirical systems are used as shear connectors for composite steel–concrete floor slabs, such as welded steel bars and U-shaped channels. However, the widespread use of these solutions represents a technical challenge, as their structural performance is not always consistent with established design standards. This study experimentally evaluates the structural behavior of different shear connectors, including both empirical and manufacturer-certified systems, following the provisions of Eurocode 4 and using the push-out test to assess shear resistance, slip stiffness, ductility, and failure mechanisms. Five connector types were analyzed: Hilti X-HVB 95 connectors and Nelson studs as commercial systems, and U-shaped sections, welded steel bars, and welded Nelson studs with E-7018 electrodes as empirical alternatives, testing a total of 15 composite specimens with three specimens per connector type. Results indicate that the highest shear resistance was achieved by the U-shaped connector (462.61 kN) and the Hilti X-HVB 95 (455.85 kN), while the lowest values corresponded to the welded steel bar connector (144.92 kN) and the welded Nelson connector (177.26 kN). In terms of slip stiffness, Nelson (36.59 kN/mm) and E-7018 welded Nelson (35.45 kN/mm) connectors exhibited the highest values, whereas the welded steel bar (10.96 kN/mm) and U-shaped connector (13.13 kN/mm) showed the lowest. These results demonstrate that both empirical and commercial connectors can achieve adequate performance to ensure composite action in floor systems. The comparative analysis supports the technical viability of selected empirical connectors and highlights their practical advantages, including material availability, ease of fabrication, and cost-effectiveness, which favor their continued application in local construction practices.

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I. INTRODUCTION

The evolution of construction has led to the development of innovative systems that improve both execution efficiency and structural performance. Among these, structural steel stands out for its rapid construction capabilities, while its combination with concrete enhances strength and compressive resistance, enabling the development of durable composite structures. [6] [7] Composite steel–concrete systems are based on the interaction between steel beams and concrete slabs, which must act together to ensure structural efficiency. This interaction relies on the use of shear connectors, which enable the effective transfer of longitudinal forces between materials and ensure compliance with design standards such as Eurocode 4. [1]

In Honduras, the absence of specific regulations and limited technical control has led to the widespread use of empirically fabricated shear connectors, such as welded steel bars and U-shaped channels, instead of manufacturer-certified systems [9]. Although these solutions are commonly applied in practice, their structural performance and compliance with international standards remain uncertain [4]. In this context, the present study experimentally evaluates the structural behavior of empirical shear connectors in comparison with commercial alternatives [8][14]. The analysis focuses on key parameters, including load-bearing capacity, slip stiffness, ductility, and shear behavior, using the push-out test methodology. The objective is to determine whether these empirical solutions can satisfy the technical requirements established by international standards and to assess their viability as safe and practical alternatives in local construction. [10]

II. METHODOLOGY

This study adopts an experimental approach to evaluate the structural behavior of shear connectors in composite steel–concrete systems. Five types of shear connectors commonly used in practice were analyzed, including both manufacturer-certified and empirically fabricated alternatives: Hilti X-HVB 95, Nelson studs, U-shaped channels, welded steel bars, and welded Nelson studs using E-7018 electrodes. A total of 15 push-out test specimens were fabricated, with three specimens per connector type, following the general provisions of Eurocode 4 [2] [5]. Each specimen consisted of a W12×45 steel section 0.80 m long, acting as the central steel member, with concrete slabs cast on both sides.

The steel surface was prepared before connector installation by cleaning and sanding the welding areas to improve bonding and welding quality. Depending on the connector type, installation was carried out by arc welding, fastening gun, or direct fixing. Reinforcement mesh measuring 0.15 m × 0.15 m was placed within the concrete slabs. Ready-mix concrete with a design compressive strength of 3000 psi was used [11]. All specimens were cast on the same day to ensure homogeneous conditions and a consistent curing age, and were cured for 25 days prior to testing. The experimental program followed the push-out test procedure to evaluate shear resistance, slip stiffness, ductility, and failure mechanisms. Theoretical resistance values were estimated using equations derived from Mechanics of Materials by Ferdinand P. Beer, specifically from the chapter on shear behavior, and were used as a reference for comparison with experimental results. [12]

According to Eurocode 4, 25 preloading cycles are recommended prior to monotonic loading; however, due to practical constraints, only 5 cycles were applied. This may influence the initial load–slip response; nevertheless, all specimens were tested under the same protocol, ensuring valid comparative results.

After the preloading stage, load was applied monotonically until failure. During testing, the applied load and the corresponding longitudinal slip were continuously recorded to generate load–slip curves for each specimen. These curves were used to compare the structural behavior of empirical and commercial connectors and to determine their main mechanical response parameters. In addition to the quantitative analysis, a qualitative assessment of the observed failure modes was conducted for each connector type. This allowed the identification of differences in structural response, failure patterns, and practical feasibility for application in local construction. (Fig 1 to 4)

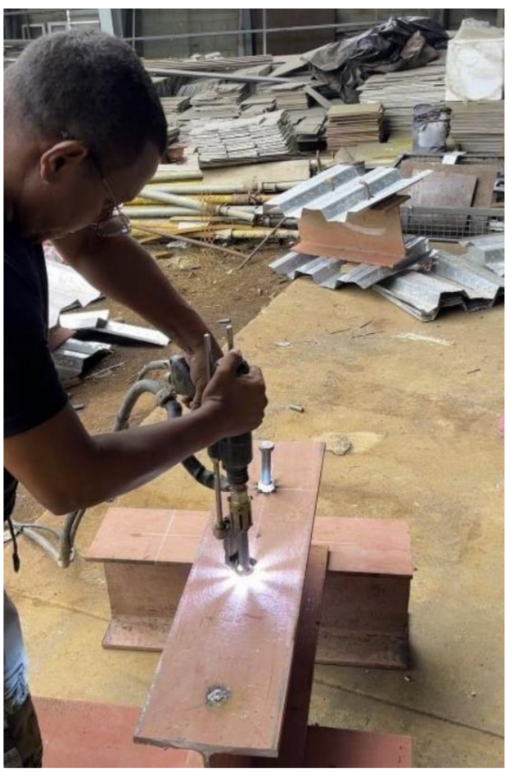

Fig. 1. Installation of Nelson stud connector using a stud welding gun

Fig. 2. Installation of steel deck sheet

Fig. 3. Formwork for composite slab test specimen

Fig. 4. Casting of concrete for composite slab test specimens

It should be noted that all test specimens were cast on the same day to ensure homogeneous conditions among the concrete slabs of each unit, guaranteeing a consistent curing age at the time of testing. This approach allowed for uniformity in the mechanical properties of concrete, minimizing variability in compressive strength associated with differences in curing time.

Prior to testing, the specimens were transported to the hydraulic press using forklifts and carefully positioned. To prevent any unintended displacement during loading, the specimens were secured using structural steel profiles and steel plates, ensuring proper alignment and stability throughout the test procedure (Fig. 5).

To measure the relative slip between the steel beam and the concrete slab, three displacement measurement devices were installed at key locations along the beam–slab interface. These devices were used to continuously record the longitudinal displacement during loading, allowing for the development of load–slip curves and the evaluation of connector behavior.

Additionally, modifications were made to the hydraulic press, which was originally designed for pipe testing, in order to adapt it to the push-out test configuration. This adaptation included the incorporation of load distribution plates placed on the steel profile to ensure a uniform application of the load and proper transfer of longitudinal shear forces to the connectors.

Fig. 5. Push-out test setup using hydraulic press

The push-out test was conducted under static loading conditions by applying a vertical load through a hydraulic cylinder until failure of the connector or significant separation at the steel–concrete interface was observed. This procedure allowed for the evaluation of the ultimate load-bearing capacity and the overall structural response of each connector type. According to Eurocode 4, it is recommended to apply 25 preloading cycles prior to the monotonic loading stage in order to simulate in-service conditions and reduce initial seating effects. However, due to practical constraints related to time and equipment limitations during the testing process, only five preloading cycles were applied. This reduced number of cycles may have influenced the initial deformation response of the specimens, particularly in the early stages of the load–slip behavior. Nevertheless, since all specimens were subjected to the same loading protocol, the comparative evaluation among connector types remains consistent and valid.

During testing, key parameters were recorded, including the maximum load carried by each specimen, the total longitudinal displacement, and the corresponding load–slip response. In addition, the failure mode of each specimen was documented, including connector fracture, concrete detachment, and slab cracking. These results were subsequently analyzed to compare the structural performance of the different types of connectors and to identify variations in behavior between empirical and commercial systems.

III. Analysis and Results

A. Strength

The U-shaped channel connector exhibited shear resistance values that exceeded the theoretical design strength in all tested specimens. For instance, the second specimen, with an expected theoretical capacity of 45.33 kN per connector, reached a maximum load of 115.65 kN per connector [7] [13]. At the system level, this corresponded to a total load of 462.61 kN. The predominant failure mechanism was characterized by concrete crushing and cracking in the contact region between the connector and the slab, in some cases accompanied by the formation of a shear plane in the surrounding concrete. These failure modes are consistent with ductile behavior, indicating that the connector maintained its load-carrying capacity until the final stages of the test. [14]

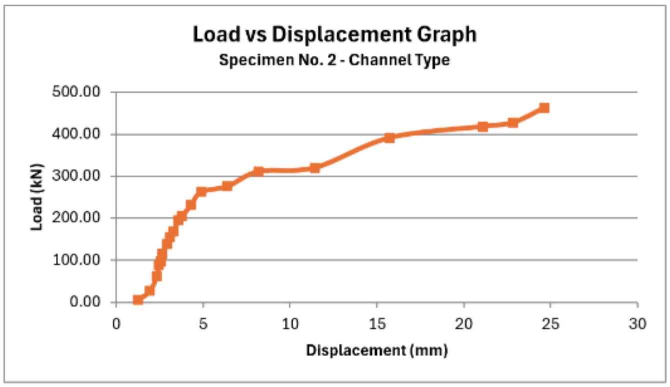

Fig. 6. Graph showing the load and displacement during the loading of Specimen No. 2, Channel Type.

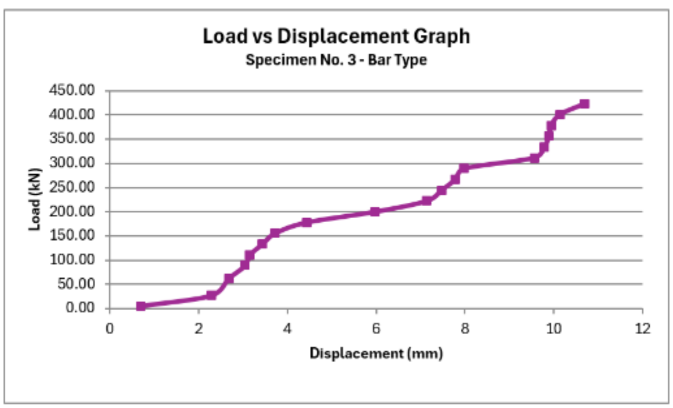

Fig. 7. Graph showing the load and displacement during the loading of Specimen No. 3, Bar Type.

The bent steel bar connector reached the target design strength in two out of the three tested specimens. For the third specimen, with an expected theoretical capacity of 53.10 kN per connector, a maximum load of 105.64 kN per connector was achieved. At the system level, this corresponded to a total load of 422.58 kN.

However, one specimen failed before reaching the target load. The observed failure mechanism consisted of a combination of a shear plane located at the weld or anchorage region and cracking and crushing of the surrounding concrete. This behavior suggests that the performance of the connector is influenced by the quality of the anchorage and the interaction between the steel and the surrounding concrete. (Fig 6 and 7)

B. Stiffness

For the U-shaped channel connector, the initial slip stiffness exhibited a wide range across the tested specimens, varying from 13.13 kN/mm in the second specimen to 38.51 kN/mm in the first specimen. [6]

For the bent steel bar connector, stiffness values ranged from 10.96 kN/mm in the second specimen to 27.65 kN/mm in the third specimen. When adequate welding and anchorage conditions were achieved, the observed performance was comparable to that of certified connectors, with failure modes dominated by concrete crushing and cracking accompanied by a secondary shear plane.

However, the first specimen, which exhibited a stiffness of 26.54 kN/mm, presented manufacturing deficiencies that led to a brittle failure characterized by the formation of a shear plane at the connection interface. This behavior negatively affected both stiffness and ductility.

The variability observed in both connector types indicates that stiffness is influenced by the quality and consistency of manufacturing and installation. Based on the slip modulus values obtained, both the U-shaped channel and bent steel bar connectors can be classified as rigid connectors, satisfying the stiffness requirements of Eurocode 4.

The highest stiffness value recorded in the tests corresponded to the first specimen of the U-shaped channel connector, reaching 38.51 kN/mm. This result indicates that, when adequate interaction between the connector and the surrounding concrete is achieved, the composite system can develop a high resistance to slip deformation during the loading phase.

Connector Type	Specimen	Stiffness (kN/mm)
Bent bar	1	26.54
Bent bar	2	10.96
Bent bar	3	27.65
Channel Type	1	38.51
Channel Type	2	13.13
Channel Type	3	25.82
Hilti X-HVB 95	1	32.38
Hilti X-HVB 95	2	32.30
Hilti X-HVB 95	3	23.90
Nelson Stud	1	18.75
Nelson Stud	2	36.59
Nelson Stud	3	19.69
N. Stud (7018)	1	32.17
N. Stud (7018)	2	35.45
N. Stud (7018)	3	23.78

TABLE I

Summary Table of Connector Stiffness

C. Ductility

According to Eurocode 4, a connector is classified as ductile when it reaches a characteristic slip of at least 6 mm. In this study, not all connectors consistently satisfied this requirement across the tested specimens. While some connectors exceeded this threshold in individual cases, the results exhibited significant variability. [13]

Fig. 8. Post-test condition of U-shaped channel connector

Fig. 9. Post-test condition of bent steel bar connector

Based on Fig. 8 and Fig. 9, the U-shaped channel connectors exhibited clear signs of large plastic deformation and bending, particularly at the welded ends, indicating significant relative displacement between the steel beam and the concrete slab during the push-out tests.

The visible distortion observed in the second and third specimens is consistent with the high slip values recorded (24.64 mm and 11.81 mm), both exceeding the 6 mm ductility requirement. A similar trend was observed for the bent steel bar connector: the second specimen reached 25.56 mm and the third specimen 10.69 mm, both satisfying the ductility criterion, while the first specimen reached only 3.82 mm and did not meet the requirement. This specimen exhibited a mode 1 failure associated with deficiencies in welding and anchorage. [14]

These results highlight the influence of fabrication quality on ductile performance, indicating that adequate welding and anchorage conditions are critical for achieving the deformation capacity required by Eurocode 4.

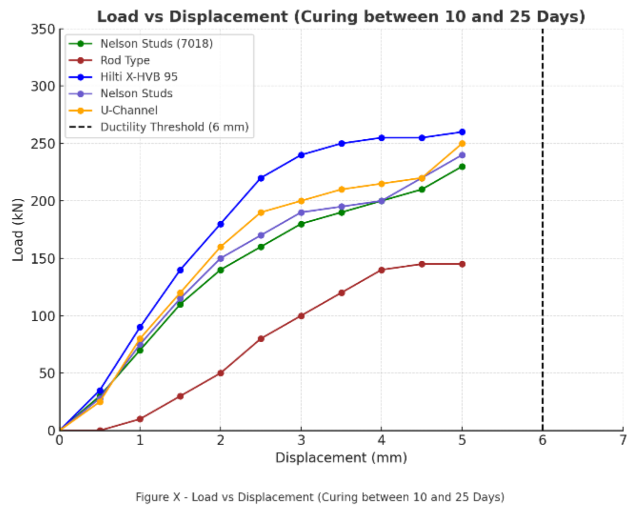

Fig. 10. Load–slip comparison for different curing ages.

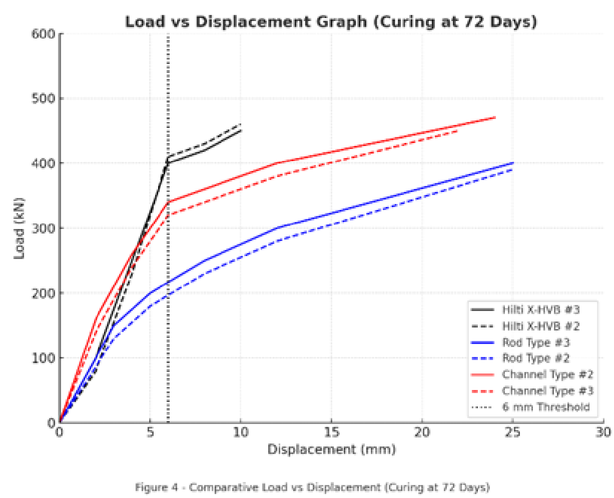

Fig. 11. Load–slip comparison at 72 days curing

These results, shown in Fig. 10 and Fig. 11, indicate that ductility in push-out tests is sensitive to concrete properties, particularly compressive strength and curing age. In several cases where the Eurocode 4 ductility requirement was satisfied, the concrete compressive strength exceeded 31 MPa and the curing age was greater than 60 days. [10] [11]

This behavior is consistent with established design principles, which relate increased concrete maturity to higher compressive strength and modulus of elasticity, contributing to improved deformation capacity of the composite system [3].

IV. CONCLUSIONS

The experimental results demonstrate that empirical U-shaped channel and bent steel bar connectors are capable of developing composite action and can meet or exceed the target design strength under the tested conditions. When properly fabricated and installed, both connector types satisfied the rigid classification criteria established by Eurocode 4 in terms of slip stiffness.

Regarding ductility, two out of three specimens for each connector type exceeded the 6 mm slip requirement. These results indicate that, under adequate material and fabrication conditions, empirical connectors can achieve deformation capacities comparable to those of commercial systems. The predominant failure mode consisted of concrete crushing and cracking combined with the formation of a shear plane, which is consistent with ductile behavior. In contrast, less favorable mode 1 failures were associated with deficiencies in welding and anchorage, highlighting the importance of quality control during fabrication and installation.

Ductility was found to be influenced by concrete properties, particularly compressive strength and curing age. Specimens that satisfied the displacement requirements generally exhibited compressive strengths above 31 MPa and curing ages greater than 60 days, indicating that concrete maturity plays a significant role in deformation capacity.

From a practical and economic perspective, empirical connectors demonstrated a favorable performance-to-cost ratio. The U-shaped channel and bent steel bar connectors showed competitive behavior compared to commercial systems such as Hilti X-HVB 95 connectors, Nelson studs, and welded Nelson studs with E-7018 electrodes.

In addition, empirical connectors offer practical advantages, including the use of locally available materials, conventional SMAW welding processes, reduced dependence on specialized equipment, and the possibility of on-site adjustments. These characteristics contribute to lower construction costs and reduced supply constraints.

Although the experimental program was conducted using a reduced number of preloading cycles compared to Eurocode 4 recommendations, the consistent application of the same loading protocol across all specimens ensures the validity of the comparative analysis. Furthermore, theoretical resistance values were estimated using formulations derived from established mechanics of materials principles, providing a complementary reference for interpreting the experimental results.

Overall, the findings support the use of empirical connectors in Honduras, provided that validated construction procedures are followed. It is recommended that push-out tests be performed when introducing design variations, and that clear specifications for welding, inspection, and quality control be established. These measures could serve as a foundation for the development of national technical guidelines for composite construction systems.

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