American Journal of Civil Engineering and Architecture, 2018, Vol. 6, No. 1, 38-45
Available online at http://pubs.sciepub.com/ajcea/6/1/5

DOI:10.12691/ajcea-6-1-5

Influence of Interlayer in Timber-Concrete Composite Structures with Threaded Rebar as Shear Connector-Experimental Study

Decroly DJOUBISSIÉ DENOUWÉ[1], Adamah MESSAN[1,*], Eric FOURNELY[2,3], Abdelhamid BOUCHAIR[1,2,3]

[1]Institut International d'ingénierie de l'Eau et de l'Environnement (2iE), Laboratoire Eco-Matériaux de Construction (LEMC), 01 BP 594 Ouagadougou 01, Burkina Faso
[2]Université Clermont Auvergne (UCA), Institut Pascal (IP), BP 10448, F-63000 Clermont-Ferrand, France
[3]CNRS, UMR 6602, Institut Pascal, F-63171 Aubière, France
*Corresponding author: adamah.messan@2ie-edu.org

Abstract The influence of interlayer on mechanical properties of timber-concrete composite structures using threaded rebar as shear connector is studied. Push-out tests are performed with two configurations of connection between timber and concrete with and without plywood interlayer: one threaded rebar and two cross-threaded rebars. The experimental study consists of push-out tests to characterize the failure modes, the load carrying capacity, and the stiffness for serviceability and ultimate limit states of the connections. The responses of the configurations with interlayer are compared with those without interlayer. The comparisons show that the presence of interlayer reduces the shear strength and the stiffness of the timber-concrete connection with threaded reinforcing bar as connector. Furthermore, based on the experimental results and using nonlinear regression, a mathematical model of each one of configurations of connection is derived which can be easily used with nonlinear FE analyses of Timber-Concrete Connection (TCC) beams.

Keywords: *timber-concrete connection, tropical wood, threaded rebar, interlayer, push-out tests*

Cite This Article: Decroly DJOUBISSIÉ DENOUWÉ, Adamah MESSAN, Eric FOURNELY, and Abdelhamid BOUCHAIR, "Influence of Interlayer in Timber-Concrete Composite Structures with Threaded Rebar as Shear Connector-Experimental Study." *American Journal of Civil Engineering and Architecture*, vol. 6, no. 1 (2018): 38-45. doi: 10.12691/ajcea-6-1-5.

1. Introduction

The timber-concrete composite system is a solution used both for the rehabilitation and reinforcement of existing timber structures and for the new constructions. Indeed, the lightness of the timber and its good tensile strength coupled with the inertia and compression strength of the concrete, through connectors, makes it possible to obtain light and resistant structures while maximizing the mechanical performances of each [1].

For new buildings, the construction of a formwork is necessary in the case of joisting with slab concrete casting. This formwork can be installed permanently between the concrete slab and the timber beams in order to make easy the realization of the floor. In rehabilitation and reinforcement of old timber floors, existing floorboards can be used as permanent formwork and interlayer between concrete slab and timber beams [2]. There is a limited number of studies on the influence of interlayer on the mechanical properties of timber-concrete connections. The most studied connection in that way is SFS screw connectors.

Van Der Linder [3] examined the effect of interlayer on SFS screw connections behaviour. Three series of push-out tests were realized, one series without interlayer, two other series using 19 mm and 28 mm of particleboard between the concrete slab and timber beam. The timber species used in the test was spruce and the concrete class was C25/30. The failure mode observed in the connection was dependent on the presence of sheeting. In the connection with interlayer, the failure was reached by withdrawal because of the reduction of the penetration length of SFS screw on timber due to the interlayer thickness. However, in the connection without interlayer, the failure is due to the fracture of the steel shaft. The strength of connection decreased by 30% and 32% with 19 mm and 28 mm of particleboard interlayer respectively, in comparison with the connection without interlayer. Moreover, the slip modulus decreased by 56% and 49% respectively.

Jorge et al [4] studied the interlayer influence on the behaviour of connections with SFS screw and lightweight aggregate concrete. They performed push-out tests using glued laminated spruce timber and two classes of lightweight aggregate concrete with and without interlayer. The interlayer of 25 mm thickness is produced with sawn timber. The results showed that the influence of interlayer on slip modulus of connection was evident, and did not depend on the quality of lightweight aggregate concrete. A decrease in strength of 3 to 10% was observed for section with interlayer when compared to those without interlayer. A decrease in slip modulus of 25 to 34% was also observed. However, with the lightweight aggregate concrete, the decrease of strength and slip modulus is not as pronounced as that of normal concrete that were tested by [3].

Moshiri et al [5] also investigated the effect of interlayer with SFS screw connector. They used Laminated Veneer Lumber (LVL) as timber joist and two types of concrete (self-compacting and normal) with a 28-days compressive strength of 35 MPa and 32 MPa respectively. A 17 mm plywood was used as interlayer between timber and concrete in push-out specimen. The results showed that the use of interlayer reduced the load capacity of self-compacting concrete and normal concrete test series by about 15% and 7% respectively. They showed also a reduction of approximately 45% in the serviceability slip modulus for both self-compacting concrete and normal concrete test series.

The influence of interlayer on the behaviour of dowel connection was studied by Dias et al [2,6]. The dowel was produced from 10 mm profiled reinforcing steel bar of steel quality S500 according to Eurocode 2. The authors used glued laminated spruce timber, C30/37 normal concrete class and floorboard interlayer of 20 mm. They realized 10 specimens for each configuration with and without interlayer. They observed that the load carrying capacity of connection decreased by around 8% when a floorboard interlayer of 20 mm was used. They also noted the decrease by about 53% of slip modulus.

These studies showed that the interlayer has some effect on the behaviour of composite concrete-timber systems more for slip modulus than for the load capacity. This influence depends on the quality of materials used including the connectors. To enrich the limited existing research, the present study examines the influence of the interlayer on the efficiency of timber-concrete composite connections using normal threaded reinforcing steel bars as connectors. The short-term load-slip behaviour considering mainly the failure mode, the shear strength and the stiffness of connections with and without interlayer are investigated through asymmetric push-out tests. The results are presented and analysed. In addition, Non-linear regression of experimental results is undertaken to derive mathematical load-slip model for timber-concrete connection with normal threaded reinforcing steel bar.

2. Materials and Methods

2.1. Materials Properties

The timber used is Kosipo (*Entandrophragma candollei Harms*) which is proposed in Burkina Faso market with the name of “red wood” because of its red brown colour. It is locally available and generally used for temporary constructions. Characterization tests carried out according to EN 408 standard [7] showed the following properties: 578.3 kg/m^3 of average density and 55 MPa of compression strength with 7% of average moisture content.

The concrete used for the push-out test specimens was manufactured in laboratory using Portland cement type CEM I 42.5 R, with a plastic consistency and a maximum size of coarse aggregate of 12.5 mm, without admixtures. Five cylinders 100x200mm were cast during the preparation of push-out specimens and tested on the day of push-out tests, i.e. at 48 days, to obtain the compression strength. The average of compression strength was 30.7 MPa and the average density was 2,386 kg/m^3. It can be considered as C20/25 strength class according to EN 206-1 standard [8].

The shear connectors were produced from reinforcing steel bar available in the local market. The strength of the steel bar was evaluated by means of tensile test. The mean value of tensile strength obtained is 331 MPa.

2.2. Connection Description

Two configurations of connection between timber and concrete were used with and without plywood interlayer. One configuration of connection consists of a simple threaded rebar screwed to the timber beam with a direction to grain of 90° (STRI and STRW). The other configuration consists of two cross-threaded rebars screwed in the timber element with a direction to grain of 90° and 120° (XTRI and XTRW). Table 1 summarizes all tested configurations and the details of the connection given in Figure 1. Rebars used as shear connectors have 12 mm of diameter, threaded over 75mm at one extremity and have a 50 mm hook at the other extremity. The thread allowed driving into the predrilled hole in timber beam. The predrilled hole was done with 9 mm diameter and 75 mm depth, which is equal to the length of threaded rebar in timber member. The hook allows to manually screw the connector in the pilot hole in the timber and also serves as anchor in the concrete. The threaded rebar had depths inside the concrete of 40 mm (without interlayer) and 30 mm (with interlayer screwed at 90°). No glue is used to fix the connector in timber in this study. Figure 2 shows the threaded rebars after screwing into the timber beam for the configurations of connection without interlayer (STRW and XTRW).

Table 1. Test Series Description

Series label	STRI	STRW	XTRI	XTRW
Threaded rebar	Simple threaded rebar at 90°		Cross-threaded rebar at 90°/120°	
Interlayer	With	Without	With	Without

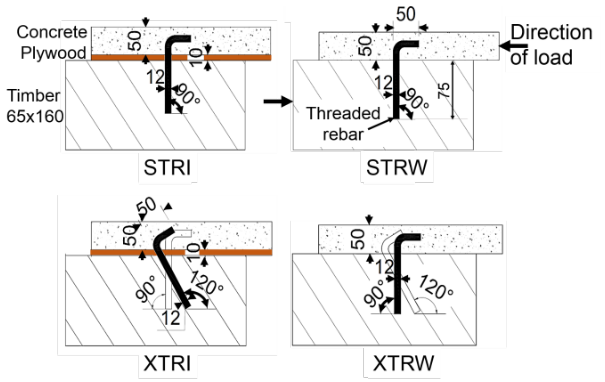

Figure 1. Configurations of Connection Tested

Figure 2. Threaded Rebars after Screwing into the Timber

2.3. Test Specimen Configuration and Test Setup

Push-out tests are essential to evaluate the behaviour of timber-concrete composite connections and indirectly the influence of the interlayer, since they provide information that leads to the prediction of the load-carrying capacity, the slip modulus, the failure modes and the load-slip diagram. The push-out tests were undertaken at the laboratory LEMC (2iE Ouagadougou). Prior to test setup choice, preliminary tests series [9] were performed to define the adequate test configuration.

The test specimens consisted of an asymmetric push-out configuration with a 60 x 160 x 350 mm^3 timber member and a 50 x 300 x 350 mm^3 concrete slab. A total of 21 specimens were tested using the experimental set-up displayed in Figure 3. Three specimens of STRI and six specimens of STRW, XTRI and XTRW connections were prepared for push-out tests. For the specimens with interlayer, a 10 mm thick plywood formwork was used. Preparation of test specimen began by predrilling the connector holes in the timber elements, followed by nailing the plywood formwork either on the top of the timber beam or on the two sides of the beam to be used only as formwork (cases without interlayer). The threaded reinforcing steel bar is then introduced in the hole, followed by the installation of mesh reinforcement of the concrete slab before the concrete pouring. After 7 days, the specimens were demoulded and were kept to indoor laboratory environment until testing.

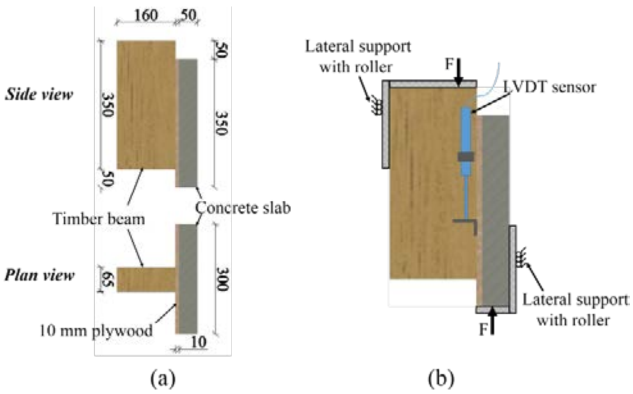

Figure 3. (a) Test Specimen Dimension; (b) Test Setup

The shear tests were performed, 48 days after the concrete pouring, following the recommendations of the European standard EN26891 [10]. Although this standard is set for timber-to-timber joints, it is widely accepted that it might be applied to timber-concrete composite connections. The shear tests were conducted at constant loading rate of 0.2 mm/s up to failure or to a maximum slip of 40 mm without initial loading-unloading phase because of limited possibilities of the testing machine used. The applied load and the corresponding relative slip between timber and concrete were measured. The relative slip was measured simultaneously at both sides of the test specimen with two LVDT sensors. The load was measured on the top of the timber member, while the relative slip was measured at the middle of the test specimens (see Figure 3). The LVDT sensors were fixed by means of glue on timber and concrete (or plywood). The compression load was applied to specimen through a steel device to provide a load distribution over the timber element and a free rotation during the test.

2.4. Characteristic Behaviour of Connections

Factors such as failure mode, strength and stiffness can characterise the behaviour of the connections. Depending upon the connection type, the failure mode can be considered ductile, fairly ductile or brittle [11]. The strength of the connection $F_{\max}$ is defined as the maximum peak-load obtained in push-out test before or at 30mm of slip according to EN 12512 European standard [12]. The stiffness, which represents the ratio between the shear force and the relative slip at the timber-concrete interface, is defined at serviceability (SLS) and ultimate limit state (ULS). The stiffness of connection at serviceability limit state $K_{0.4}$ and at ultimate limit state $K_{0.6}$ are the mean secant slip moduli at 40% and 60% of maximum load, respectively as shown in Figure 4 [13] and given by the equations (1) and (2).

$$K_{0.4} = \frac{0.4F_{\max}}{v_{0.4}} \quad (1)$$

$$K_{0.6} = \frac{0.6F_{\max}}{v_{0.6}} \quad (2)$$

Where $v_{0.4}$ and $v_{0.6}$ correspond to the slips at 40% and 60% of $F_{\max}$.

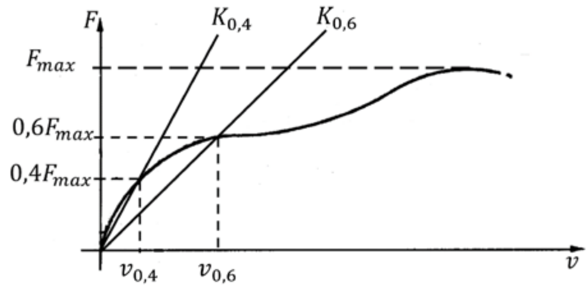

Figure 4. Definition of Shear Strength and Stiffness by [13]

3. Results and Discussions

The load-slip curves for STRI and STRW series connections are shown in Figure 5 and those of XTRI and XTRW series are shown in Figure 6. Each experimental curve given in Figure 5 and Figure 6 represents the average of the two LVDTs used in each specimen. The load-slip behaviour of all series connections was consistent. They showed a large plastic deformation capacity for all the series, which is close to the observations made for similar connection such as dowel-type fastener [14]. To examine the influence of interlayer, the specimens with the same configuration of connection are compared. It can be observed that STRI series connections with interlayer is characterized by a maximum load capacity F_{max} lower than that of STRW series without interlayer. The same observation can be made comparing XTRI and XTRW series connections.

The load-slip curves of all STRI and STRW series connections present three parts. The first part is characterised by the increase of load with a low slip, followed by the second part with a gradual increase in load and large slip up to the maximum load. At the last part, a decrease of load with the increase of slip is observed but without full failure. It seems that the end of the first part denote the yielding of the steel bar in the connection and the beginning of the plastic hinges development on threaded rebar embedded on the timber hole.

For XTRI and XTRW connections, the load-slip diagram can be represented by two parts (see Figure 6). The first part starts with a sharp increase in the load followed by the second part representing a ductile plastic behaviour with a slight fluctuation in load without full failure plastic hinges can be identified on the threaded reinforcing steel bar of STRI connection: one in timber beam and one at the interface between concrete slab and formwork (Figure 7a). On the threaded reinforcing steel bars of STRW and XTRI connections, two plastic hinges are observed: one in timber beam and the other at the concrete-timber interface (Figure 7b and c). However, only one plastic hinge was identified on threaded reinforcing steel bar of XTRW connection (Figure 7d).

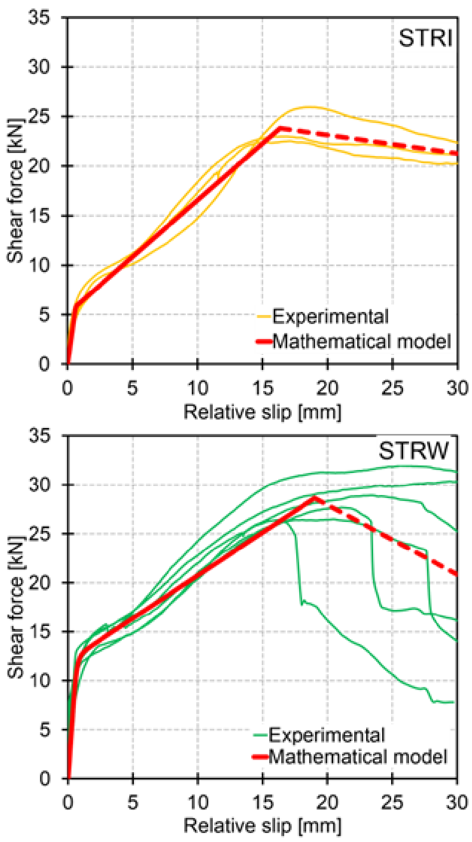

Figure 5. Experimental load-slip curves with mathematical model for STRI and STRW connections

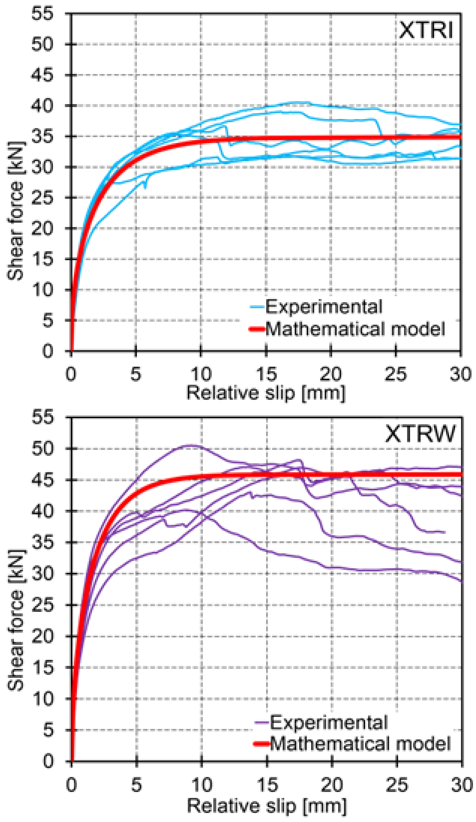

Figure 6. Experimental load-slip curves with mathematical model for XTRI and XTRW connections

Visible cracking was observed in the concrete slab to specimen of cross-threaded rebars connection with and without interlayer as shown in Figure 8, owing to the fact that this connection was strong enough to cause damage in the concrete. No visible cracking and no damage were seen in concrete slab of simple threaded rebar connection (STRI and STRW) and slabs remained intact by end of push-out test.

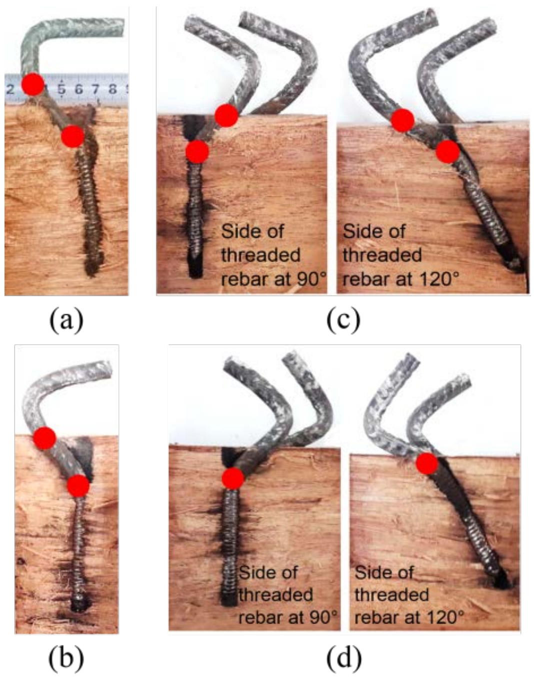

Figure 7. Failure modes of test series: plastic hinges in threaded rebar and embedment of timber; (a) STRI; (b) STRW; (c) XTRI; (d) XTRW

Figure 8. Cracking in concrete slab (XTRW - cross-threaded rebar connection without interlayer)

3.2. Strength Analysis

The shear strength represented by maximum load F_{max} for different test series is given in Table 2. The range, the standard deviation (σ) and the coefficient of variation (CoV) are also presented for all the tested series of connection. Results achieved for maximum load for each series are quite homogeneous, with coefficient of variation equal to 8% which is lower than 10%.

The simple threaded rebar connection with interlayer STRI gives the lowest shear strength compared to all others tested connection (F_{max} = 23.8 kN), followed by the simple threaded rebar connection without interlayer STRW (F_{max} = 28.6 kN). The cross-threaded rebars connection without interlayer XTRW gives the highest value of shear strength (F_{max} = 45.9 kN). The shear strength of the cross-threaded rebars connection with interlayer XTRI is equal to 36.3 kN. Thus, the mean value of strength for the connections with interlayer is between 79 % and 83 % that of the connections without interlayer.

Table 2. Shear Strength of Test Series

Test series	Number of Specimens	Shear strength F_{max} [kN]			
		Range F_{max}	Average	σ	CoV
STRI	3	22.5 – 25.9	23.8	1.8	8%
STRW	6	26.4 – 31.9	28.6	2.2	8%
XTRI	6	32.8 – 40.5	36.3	3.1	8%
XTRW	6	40.1 – 50.5	45.9	3.7	8%

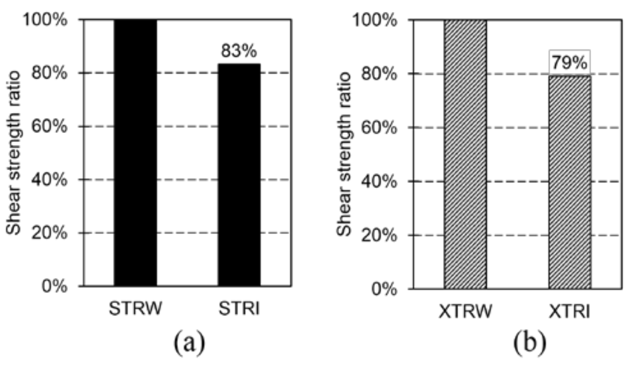

Figure 9. Comparison of shear strength mean values for test series; (a) Simple threaded rebar connection; (b) cross-threaded rebars connection

The Figure 9 shows the shear strength comparison for all the tested series. The comparison is made between the mean values of shear strength of each configuration of connection without and with interlayer: series STRW compared to STRI and series XTRW compared to XTRI. The use of interlayer reduced the shear strength of the simple threaded rebar connection and the cross-threaded rebars connection by about 17% and 21%, respectively.

3.3. Stiffness Analysis

The average values of stiffness corresponding to serviceability limit state $K_{0.4}$ and ultimate limit state $K_{0.6}$ for each configuration of connection are reported in Table 3. The range, the standard deviation (σ) and the coefficient of variation (CoV) are also reported for all the tested series of connections. The coefficient of variation (CoV) of $K_{0.4}$ ranges between 23% and 38%, and that of $K_{0.6}$ ranges between 17% and 29%.

Table 3. Stiffness of Test Series

Test series	N.	Stiffness [kN/mm]				
		Case	Range	Average	σ	CoV
STRI	3	$K_{0.4}$	1.9 – 4.1	2.9	1.1	38%
		$K_{0.6}$	1.5 – 2.1	1.8	0.3	17%
STRW	6	$K_{0.4}$	8.9 – 22.7	15.4	5.5	35%
		$K_{0.6}$	2.3 – 4.4	3.1	0.8	25%
XTRI	6	$K_{0.4}$	18.2 – 29.6	23.8	5.4	23%
		$K_{0.6}$	11.4 – 19.1	15.5	3.6	23%
XTRW	6	$K_{0.4}$	24.0 – 40.0	31.9	7.7	24%
		$K_{0.6}$	13.9 – 30.6	21.4	6.1	29%

The simple threaded rebar connection with interlayer STRI gives the lowest value of stiffness compared to all others tested connection at both the serviceability and ultimate state ($K_{0.4}$ = 2.9 kN/mm and $K_{0.6}$ = 1.8 kN/mm). The simple threaded rebar connection without interlayer STRW shows significant increase of stiffness at serviceability limit state ($K_{0.4}$ = 15.4 kN/mm) but with a decrease at ultimate limit state ($K_{0.6}$ = 3.1 kN/mm). In addition, the cross-threaded rebars connection with interlayer XTRI shows a mean value of stiffness higher than that of the other tested connections ($K_{0.4}$ =23.8 kN/mm and $K_{0.6}$ =15.5 kN/mm). Finally, in comparison with all the tested specimens, the cross-threaded rebars connection without interlayer XTRW gives the highest values of stiffness at both serviceability and ultimate state ($K_{0.4}$ = 31.9 kN/mm and $K_{0.6}$ = 21.4 kN/mm). This trend is quasi similar to that of the shear strength.

The Figure 10 shows the stiffness comparison for different test series. The comparison is made considering the mean values of stiffness for each configuration of connection without and with interlayer at each limit state (serviceability and ultimate state). The influence of interlayer on the stiffness is striking, particularly for the simple threaded rebar connection. Results show a decrease in the stiffness at serviceability state $K_{0.4}$ of 81% for the simple threaded rebar connection with interlayer STRI when compared to those without interlayer STRW. At ultimate state, the decrease of the stiffness $K_{0.6}$ is 42%. For the cross-threaded rebars connection with interlayer XTRI, results show a decrease in the stiffness of 25% and 28% at serviceability and ultimate state respectively when compared to those without interlayer.

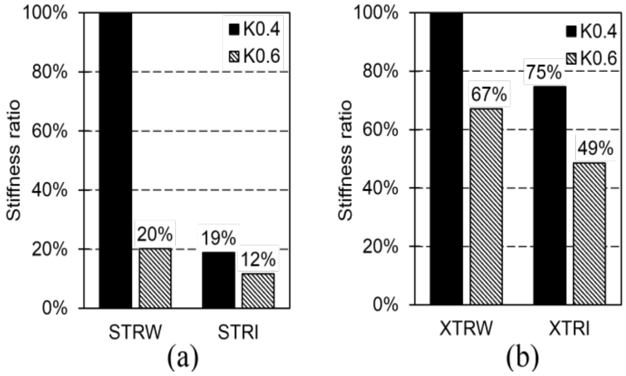

Figure 10. Comparison of Stiffness mean values for test series; (a) Simple threaded rebar connection; (b) cross-threaded rebars connection

4. Mathematical Model for Shear-Slip Behaviour of Connections

In this section, a mathematical expression for each one of experimental connection tests series is proposed using the mean load-slip curves of connections. Such mathematical model can be used to represent the connection behaviour in finite element modelling, as made by [15], or in specific programs for non-linear analyses of timber-concrete composite beams, as reported by [16]. The general trends of load-slip behaviour for STRI, STRW, XTRI and XTRW connections are discussed and then the mathematical expressions, which can properly represent the load-slip behaviour of connection, are derived. Depending on the trend of the experimental load-slip curve for different connections, different models can be developed. These models originally developed and used for steel-concrete composite beams and semi-rigid steel connections. The average of experimental shear force versus relative slip curves of each configuration of connection tested was fitted with an analytical curve (Figure 5 and Figure 6).

The load-slip curves of STRI and STRW connections can be divided into three stages as shown in Figure 5. The early stage of the curve starts with a sharp increase in the load level and represents the initial stiffness k_0 of the connection. The first stage of behaviour is followed by strain-hardening stage with the stiffness k_p which is associated with a gradual increase in load level and a large slip up to the maximum load. The third stage starts after the peak load and evidently manifested by a drop in the load. With regard to the load-slip behaviour of STRI and STRW configurations of connection, the first two parts of the load-slip curve follows a nonlinear curve up to maximum load capacity of the connection. They can be adequately represented by the Richard-Abbott model [15] given by equation 3.

$$F = \frac{\left(k_0 - k_p\right)|s|}{\left[1 + \left|\frac{\left(k_0 - k_p\right)|s|}{F_0}\right|^n\right]^{1/n}} + k_p|s| \text{ for } s \le s_p \qquad (3)$$

where k_0 is the initial stiffness, k_p is the strain-hardening stiffness, F_0 is a reference shear force, n is a parameter related to the sharpness of the curve, F is the shear force, s is the slip, s_p is the slip at maximum load capacity of connection $F_{\max}$ (Figure 11). The post-peak behaviour of STRI and STRW connections is described by a linear curve with negative slope given by equation 4.

$$F = as + b \text{ for } s_p \le s \le s_u \qquad (4)$$

Where s_u is the maximum slip (all connections tested have a maximum slip exceeding 30 mm); and a and b are constants.

For XTRI and XTRW connections, the load-slip diagram can be represented by two parts (see Figure 6). The load-slip response of these connections can be approximated by Ollgard's model which is much used by some researchers for different connections [11,17,18]. Ollgard's model is given by equation 5.

$$F = F_{\max}\left(1 - e^{-\beta s}\right)^{\alpha} \qquad (5)$$

Where $F_{\max}$ represents the maximum shear strength of connection; and α and β are parameters which control the curvature of function.

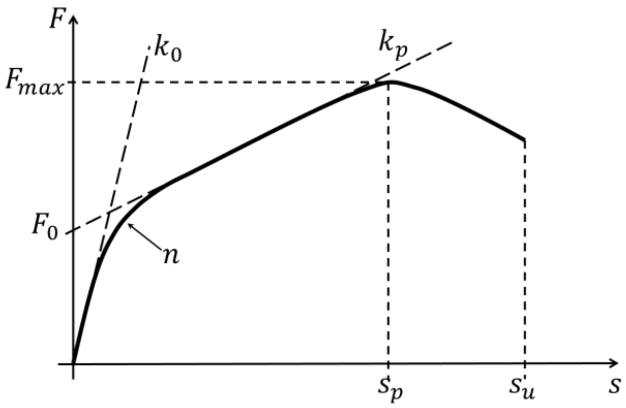

Figure 11. Parameters of Richard-Abbott model

For each configuration of connection, the fitted curve is shown in Figure 5 and Figure 6. The corresponding parameters are listed in Table 4 with R-square coefficient of nonlinear part (Pre-peak behaviour) to show the error between the average of experimental results and the proposed models.

Table 4. Parameters for mathematical model of the load-slip curves of connections

Connections	Pre-peak behaviour				Post-peak behaviour		
	Model	Parameters	Units	R^2	Model	Parameters	Units
STRI	Richard-Abbott	F_0 = 5.1	kN	0.994	Linear	a = - 0.19	kN/mm
		k_0 = 9.36	kN/mm				
		k_p = 1.14	kN/mm				
		n = 23.63	-			b = 26.9	kN
		s_p = 16.3	mm				
STRW	Richard-Abbott	F_0 = 12.0	kN	0.980	Linear	a = - 0.71	kN/mm
		k_0 = 19.20	kN/mm				
		k_p = 0.88	kN/mm				
		n = 4.97	-			b = 42.13	kN
		s_p = 19.0	mm				
XTRI	Ollgard	F_{max} = 36.3	kN	0.998	-	-	-
		α = 0.49	-				
		β = 0.31	mm^{-1}				
XTRW	Ollgard	F_{max} = 45.9	kN	0.990	-	-	-
		α = 0.43	-				
		β = 0.56	mm^{-1}				

5. Conclusion

In this study the effect of interlayer on the behaviour timber-concrete composite system with threaded rebar as shear connection is analysed. In fact, the interlayers are generally used both in rehabilitation of existing structures and new constructions.

The experimental series of push-out tests were performed on two different configurations of connections, one simple threaded rebar screwed in the timber beam with an angle to grain of 90° and two cross-threaded rebars screwed with an angle to grain of 90° and 120°, with and without interlayer. The results obtained in terms of load-slip responses, shear strength, stiffness and failure mode were compared.

The general load-slip curves of connections with interlayer indicate a similar tendency as without interlayer. The general failure mode of test series was the development of plastic hinges on the threaded rebars with embedment of timber under the connector. The main conclusion of this study is that the presence of interlayer reduced the shear strength and the stiffness of the composite timber-concrete with threaded rebar connection. On the simple threaded rebar connection and the cross-threaded rebars connection, the reduction of shear strength is about 17% and 21%, respectively. The reduction of stiffness is significant for simple threaded rebar with about 81% at serviceability limit state. For cross-threaded rebar with interlayer, the reduction of stiffness at serviceability and ultimate limit state are of 25% and 28% respectively when compared to those without interlayer.

In addition, a mathematical model has been derived to represent the load-slip curves of the tested connections using nonlinear regression. The developed models can be easily used in finite elements codes and/or for nonlinear analysis of timber-concrete composite systems with threaded rebar as shear connection. This system of connexion is simple to use and can be easy to reproduce in the local markets with limited access to sophisticated connectors.

Acknowledgements

The authors gratefully acknowledge the financial support of Deutscher Akademischer Austausch Dienst (DAAD). They would like to express their gratitude to all the staff of the platform MSGC (Mécanique et Structures de Génie Civil) of Polytech Clermont-Ferrand for their help and technical support. Finally, not the least, the authors wish to thank Mrs Marcelle Audrey KOUAM TEGUIA for her contribution in this project.

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