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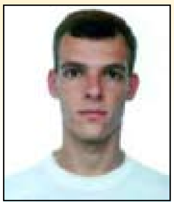
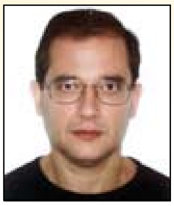
Comparative Study of Longitudinal Shear Design Criteria for Composite Slabs

Estudo Comparativo dos Critérios de Dimensionamento ao Cisalhamento Longitudinal em Lajes Mistas de Aço e Concreto

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Abstract

ABNT NBR 8800 (2008) prescribes two longitudinal shear design criteria for composite slabs with ribbed decking: m-k method and partial interaction method. The m-k method is considered the worldwide standard method. In this method, the longitudinal resistant shear strength is obtained from linear regression of test results. The partial composite method is an alternative to the m-k method and shall be used only for composite slabs with a ductile behavior. In this scenario, the objective of this paper is to compare these two methods with respect to test results of full size composite slabs employing steel-deck MF 50 manufactured by METFORM. The analysis of the comparative study shows good correlation between the two methods with respect to the prediction of the ultimate strength of the tested composite slabs.

Keywords: *composite slabs, ribbed decking, longitudinal shear.*

Resumo

A ABNT NBR 8800 (2008) permite dois critérios para avaliação da força cortante longitudinal resistente última em lajes mistas de aço e concreto: método m-k e método da interação parcial. O método m-k é o método considerado internacionalmente como padrão para o cálculo dessa força cortante longitudinal resistente. Neste método, a resistência das lajes é obtida por regressão linear dos resultados de ensaios realizados com fôrma de uma mesma espessura. O método da interação parcial, por outro lado, surge como alternativa ao método m-k, para melhor explorar o comportamento dúctil dos perfis de fôrma de aço disponíveis no mercado, os projetos de mossas mais bem elaborados e a utilização de vãos maiores. Dentro deste cenário, o objetivo deste trabalho é fazer uma análise comparativa entre estes dois critérios. Para atingir este objetivo, lajes mistas, em escala natural e com diferentes dimensões de vãos e altura total, foram construídas e testadas, na condição de simplesmente apoiadas. A fôrma de aço incorporada utilizada foi o steel-deck MF 50 fabricado pela METFORM. A análise dos resultados revela valores similares da força cortante longitudinal resistente última entre os dois critérios para a fôrma de aço incorporada utilizada.

Palavras-chave: *lajes mistas, fôrma de aço incorporada, cisalhamento longitudinal.*

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1. Introduction

ABNT NBR 8800 (2008) prescribes two longitudinal shear design criteria for composite slabs with ribbed decking: ***m-k*** method and partial interaction method. The method ***m-k*** is considered worldwide the standard method for the calculation of the longitudinal resistant shear force. In this method, this longitudinal shear force in composite slabs is calculated by a semi-empiric equation, which relates the nominal shear strength with the experimental parameters obtained from tests performed on decks of the same thickness. The partial interaction method was developed as an alternative to the method ***m-k*** for ribbed decks with a ductile behavior and/or with better-designed embossments and slabs with larger spans. Although more laborious than the method ***m-k***, the partial interaction method also allows the inclusion of reinforcing bars in the positive bending moment regions as well as the contribution of shear connectors located on the girders supporting the composite slabs.

Based on this scenario, the objective of this paper is to present a comparative analysis between these two design criteria. To reach this objective, full size simple supported composite slabs with different total heights and spans were built and tested at Federal University of Minas Gerais (Brendolan, 2007). The employed ribbed decking was steel-deck MF 50 manufactured by METFORM. It is worth mentioning that similar studies to the one presented herein were done by Lopes and Simões (2008) and Calixto *et al.* (1998).

2. Evaluation Methods for the Longitudinal Shear Strength

2.1 The m-k Method

In this paper, it is used the expression prescribed by ABNT NBR 8800 (2008) given by equation 1.

$$V_R = b \cdot d_f \cdot \left[\left(\frac{m\, A_{F,ef}}{b\, L_s} \right) + k \right] \qquad (1)$$

where:

V_R is the longitudinal shear strength force, in N, corresponded to a composite slab width of 1000 mm;

b is the composite slab width, set equal to 1000 mm;

d_f is the distance, in mm, between the centroidal axis of the profiled steel sheeting and the extreme fiber of the composite slab in compression;

$A_{F,fe}$ is the effective cross-sectional area of profiled steel sheeting, in mm^2, corresponded to a width of 1000 mm;

L_s is the shear span, in mm; and

m and k are empirical factors, derived from tests, for design shear resistance.

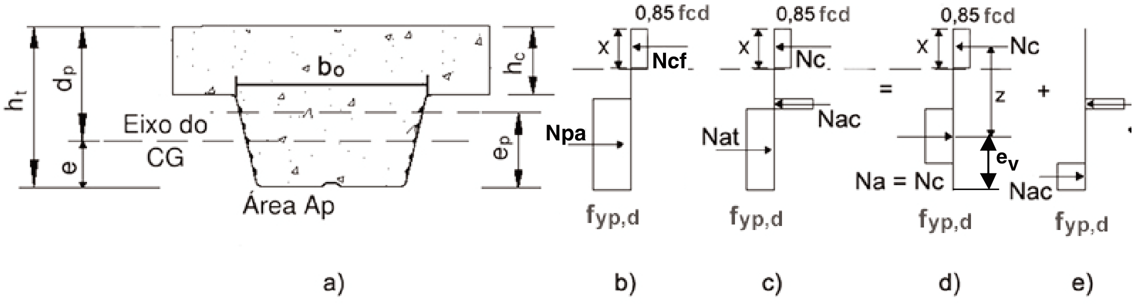
The method consists in rewriting equation 1 in the form $Y = m \cdot X + k$, where $X = \dfrac{A_{F,ef}}{b\, L_s}$ and $Y = \dfrac{V_{ut}}{b \cdot d_f}$. In this last relation, V_{ut} is the longitudinal resistant shear force, per meter of width, obtained from the experimental tests. With the values of *X* and *Y* a linear regression analysis, employing the least square method, is done from which the ***m-k*** parameters are obtained. This analysis is always done separately for each thickness of profiled steel sheeting.

2.2 The Partial Interaction Method

ABNT NBR 8800 (2008) also presents the partial interaction method and suggests the use of EUROCODE 4 (2004) procedures. These procedures are presented next.

Partial interaction between the concrete and the steel sheeting always occurs in composite slabs fabricated with steel deck MF 50. In this situation, there exists a relative horizontal displacement between these elements, which in turn generates two neutral axes: one in the concrete and another in steel sheeting. The normal stress diagram in this case is shown in figure *1.c*, where one can see the compressive normal force (N_c) in the concrete and the compressive (N_{ac}) and tensile (N_{at}) normal forces in the steel sheeting. For easy

Figure 1 – Stress distribution on a typical cross-section of a composite slab



N_{cf} = compressive normal force in the concrete flange with full shear connection
N_{pa} = tensile normal force in the profile steel sheeting with full shear connection
e_p = distance from the plastic neutral axis of sheeting to the extreme fiber of the composite slab in tension
e_v = distance from the extreme fiber of the composite slab in tension to the tensile force Na

visualization and better understanding, these forces were divided as illustrated in figures *1.d* and *1.e*. The tensile normal force N_{at} in the sheeting is divided into the forces N_a and N_{ac}, where N_a equilibrates the compressive force N_c in the concrete, while and N_{ac} counteracts the normal compressive force in the superior region of the steel sheeting. Combining the effects of these forces, the nominal resistant moment can be determined using equation 2.

$$M_{pR} = N_c \cdot z + M_{pr} \tag{2}$$

Figure *1.e* shows that the equal and opposite normal forces N_{ac} generate the resistant bending moment M_{pr} which is the effective plastic resistant moment M_{pa} of the steel sheeting, reduced by the effect of the tensile normal force $N_a = N_c$. The relationship between M_{pr}/M_{pa} and N_c/N_{pa} depends on the sheeting geometry and, according to EUROCODE 4 (2004), can be calculated by equation 3.

$$M_{pr} = 1{,}25 \cdot M_{pa} \cdot \left(1 - \frac{N_c}{N_{pa}}\right) \leq M_{pa} \tag{3}$$

The compressive normal force N_c in the concrete shown in figure *1.d* is smaller than N_{cf}: therefore, the height of compressive stress block in the concrete is given by to equation 4.

$$x = \frac{N_c}{b \cdot (0{,}85 \cdot f_{cd})} \leq h_c \tag{4}$$

The lever arm z is variable and depends on the relation N_c/N_{pa}. For intermediary situations, where $0 < \frac{N_c}{N_{pa}} < 1$, the lever arm z can be calculated according to equation 5.

$$z = h_t - e_v - 0{,}5 \cdot x \tag{5}$$

where e_v varies with respect to N_c/N_{pa} ratio. The value of e_v can be estimated by the linear relationship shown in equation 6.

$$e_v = e_p - (e_p - e) \cdot {}^{N_c}\!/_{N_{pa}} \tag{6}$$

Thus,

$$z = h_t - 0{,}5 \cdot x - e_p + (e_p - e) \cdot {}^{N_c}\!/_{N_{pa}} \tag{7}$$

According to Johnson (1994), this procedure has been validated through experimental tests with the lever arm z given by equation 7.

Based on the experimental result of each composite slab tested, the degree of shear connection η can be evaluated. With this value, the compressive normal force N_c (= η N_{cf}) being transferred from the steel sheeting to the concrete along the shear span can then be calculated. Thus, the resistant shear stress τ_u is determined by equation 8.

$$\tau_u = \frac{\eta \cdot N_{cf}}{b \cdot (L' + L_0)} \tag{8}$$

where b is the width of each composite slab tested and L_0 is the length of the overhang, which in this case is equal to 50 mm. If the effect of friction in the support regions is considered, EUROCODE 4 (2004) recommends a modification on equation 8, which is given by equation 9.

$$\tau_u = \frac{\eta \cdot N_{cf} - \mu \cdot V_{ut}}{b \cdot (L' + L_0)} \tag{9}$$

where V_{ut} is the ultimate resistant shear force obtained from each experimental test and μ is the coefficient of friction set equal to 0.5.

The degree of shear connection for each composite slab tested was determined using the real dimensions of the slabs and steel sheeting as well as the actual concrete and steel strength measured during the experimental program. The concrete compressive strength f_{cm}, according to EUROCODE 4 (2004), is the mean of the measured values during the tests. The magnitude of the bending moment corresponds to the ultimate value measured in each slab test at the section under the point load. The value of this moment includes the effects of the ultimate load applied by the hydraulic ram, of the composite slab self-weight and of the weight of the loading apparatus.

Tested Composite Slabs Characteristics

For this study, eight composite slabs were tested. The characteristics of each slab are presented in table 1.

The profiled sheeting used was steel deck MF 50 manufactured by the METFORM S. A. Its cross-sectional details and dimensions are shown in figure 2. This steel sheeting has a trapezoidal form with embossments, which provide the mechanical interlock mechanism for the composite interaction with concrete flange. In this study, steel sheeting with nominal thickness of 1.25 mm was employed. The profiled effective cross-sectional area $A_{F,ef}$ is equal to 1587 mm^2 per meter of width. The steel employed in the manufacturing of sheeting had average yield strength of 345 MPa and a modulus of elasticity of 200233 MPa.

Ready-mixed concrete was used in casting the composite slabs. The specified characteristic compressive strength (f_{ck}) was equal to 20 MPa. At each slab test, the concrete compressive strength was evaluated; the measured values were always larger than the specified strength.

Table 1 – Composite Slabs Characteristics

Series	Prototype number	Steel sheeting thickness (mm)	Slab span (mm)	Shear span (mm)	Slab overall height (mm)
A	1	1,25	1800	450	100
	2				
	3				
B	4	1.25	1800	600	120
C	5	1.25	1800	600	140
D	6	1.25	3600	900	160
	7				
	8				

4. Test Set-up and Instrumentation

The loading apparatus consisted of steel beams as shown in figure 3. A hydraulic ram, attached to a steel frame, was used to apply load to the system of steel beams. Each composite slab was tested as simply supported with two line loads equidistant from the end supports. Under each line load, rubber pads were used to distribute the loads uniformly. Any undesirable longitudinal restriction was eliminated by the roller and pin supports acting together with the spherical hinge under the hydraulic ram.

The loading scheme was monotonic. Midspan deflections and end slips at both supports were measured at each load step. Strains in the upper and lower portion of the steel sheeting at midspan were also evaluated. A computerized data acquisition system was used.

In each test, a pre-load was initially applied to the composite slab. After the removal of this pre-load, the first displacement and strain readings were taken. Loading was then applied incrementally. For loading values above the cracking moment, displacement and strain readings were taken only after the slab was stabilized.

Figure 2 – Profiled steel sheeting characteristics

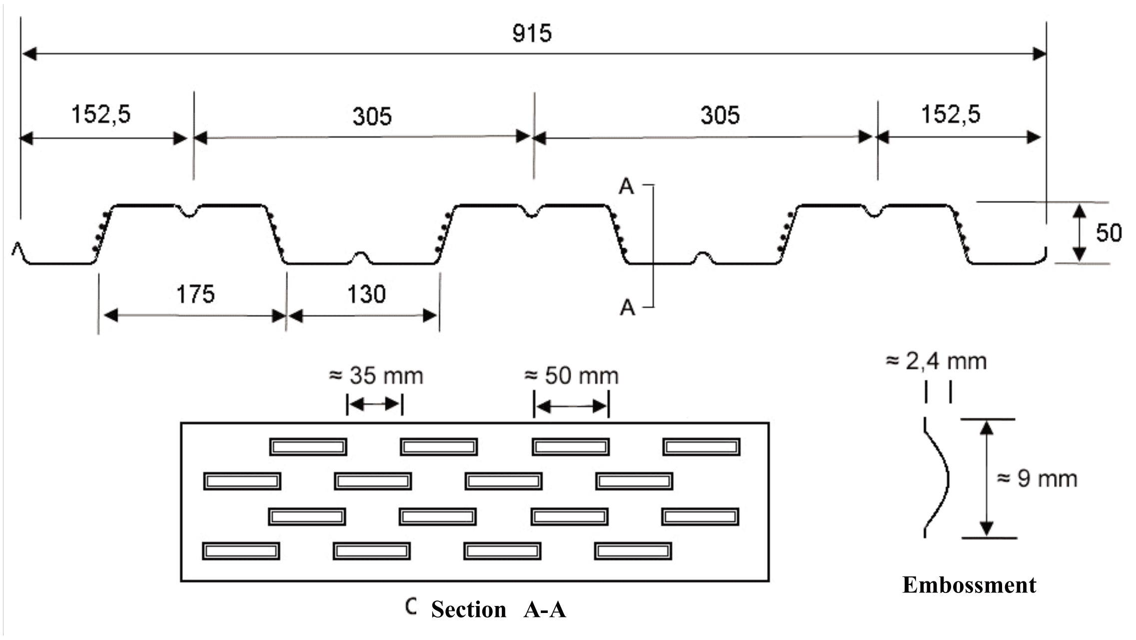
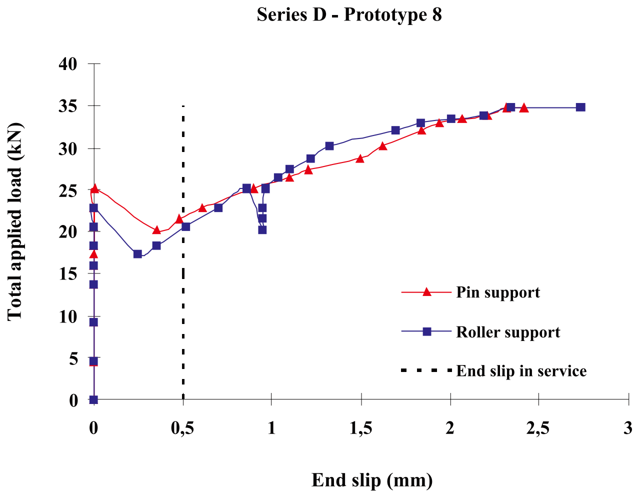


Figure 3 – Test set-up

Figure 5 – Series D – Prototype 8 – Load versus end slip



5. Test Results and Analysis

In all the tests, the first visible cracks formed in the proximities of the line loads. From this instance on, extensive cracking was noticed in between the two line loads.

A typical load versus midspan deflection relationship is shown in figure 4 for two different specimens: Series A prototype 2 and Series B prototype 4. The analysis of these results indicates that both slabs have initially a larger stiffness. With increasing loads, cracking on the concrete occurs reducing the slabs rigidity and consequently generating larger midspan deflections for the same load increment. The limit established by EUROCODE 4 (2004) for the maximum deflection in service (span/250) is equal to 7.2 mm in this case. The corresponding measured loads to this limit were about 37 kN for both specimens.

The load versus end slip relationship for prototype 8 of Series D is presented in figure 5. This plot shows at first null values for both end slips indicating complete chemical bond and full composite action between the concrete and the steel sheeting. After the concrete has cracked, partial interaction occurs since the chemical bond is lost and the mechanical interlock mechanism, provided by the embossments, is not strong enough to transfer the total shear stresses between the sheeting and the concrete. Consequently, there is a relative displacement or slip between them. This behavior is characteristic of the profiled steel sheeting used herein and was observed in all tests.

Figure 6 presents the load versus midspan strains in the steel

Figure 4 – Load versus midspan deflection

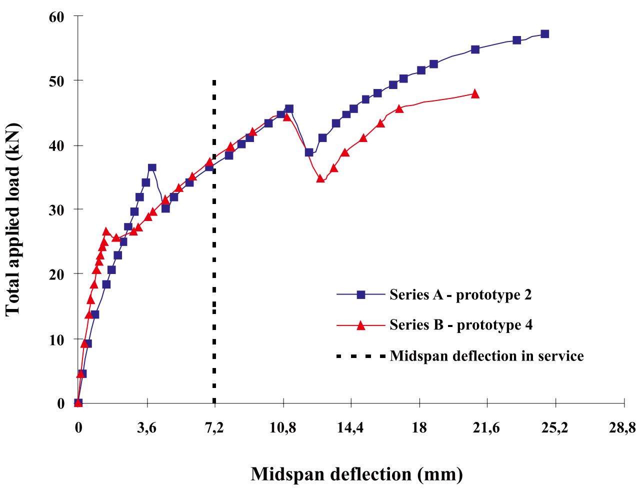
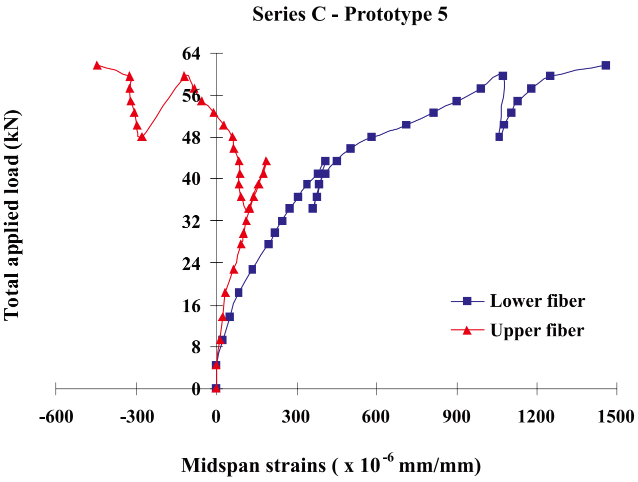


Figure 6 – Series C – Prototype 5 – Load versus midspan strains on the steel sheeting



sheeting for prototype 5 of Series C. These strains were measured in the upper and lower fibers. Tensile strains have positive values while compressive ones negative. As expected, the lower fiber exhibited tensile strains up to failure. The upper fiber, on the other hand, showed a reversal in its strain from tension to compression. This compressive strain value in the upper fiber indicates the existence of a second neutral axis below the sheeting top fiber, which characterizes partial interaction behavior and the low shear transfer efficiency provided by the embossments, used, which in turn cause the slip between the concrete and the steel-deck.

It is interesting to point out that the failure mode in all cases was shear bond. This rupture mode is characterized by the shear connection failure between the embossments in the sheeting and the concrete along the shear span. Although composite action was lost, the concrete, in no instant, became completely separated from the steel sheeting as shown in figure 7. In other words, the shear transfer mechanism provided by the embossments was capable of holding concrete and sheeting together even after the ultimate load was reached.

The composite slab test results are present in table 2. In the table, P_{ue} corresponds to the ultimate applied load, SW_{slab} the composite slab self-weight and V_{UT} the ultimate shear force per meter of width.

Based on those test results, the values of $X = \dfrac{A_{F,ef}}{b\,L_s}$ and $Y = {}^{V_{ut}}\!/_{b.d_f}$ necessary to the *m*-*k* method were calculated as previously described. The values of the slope ***m*** and of the intercept ***k*** of the equation $(Y = m.X + k)$ were determined by linear regression. Substituting these values in the equation 1, the resistant shear force V_R for each slab was calculated. These values are next compared to the test measured ones in order to evaluate their correlation. Table 3 presents all these results and comparison.

Figure 7 - Series A – Prototype 2 - Observed end slip at ultimate applied load

The Canadian Steel Sheet Building Institute (CSSBI, 2002) recommends that the ratio of the resistant shear force V_R to test measured value V_{UT} for each specimen shall be between the limits from 0.85 to 1.15. If the V_R/V_{UT} ratios are outside these limits, ***m*** and ***k*** must be reduced by 5 %. As it can be seen in the table 3, the found ratios in all cases are within those limits.

Before applying the partial interaction method, it is necessary initially to determine the position of the neutral axis e_p and the value of the plastic moment M_{pa} of the steel sheeting. In determining the values, the concrete average compressive strength was set equal to 30.5 MPa, while the yield strength and modulus of elasticity of the steel in the sheeting to 345 MPa and 200233 MPa respectively. The position of the neutral axis e_p and the value of the plastic moment M_{pa} were calculated according to ABNT NBR 14762 (2001) prescribed procedure. Due to the existence of the embossments, a reduction in the sheeting cross-sectional area was considered. The values determined for e_p (measured from the lower fiber) and M_{pa} were 25.7 mm and 10.11654 kNm/m, respectively.

The test result for each specimen as well as the degree of shear connection η and the resistant shear stress τ_u are shown in table 4. In the table, V_{UT} is the test ultimate shear force and M_{UT} is the

Table 2 – Composite slab test results

Series	Prototype	Shear span (mm)	Slab width (mm)	Overall slab height (mm)	P_{ue} (kN)	SW_{slab} (kN/m^2)	V_{ut} (kN/m)
A	1	450	949	73.74	53.95	1.93	30.16
	2	450	948	73.04	60.81	1.92	33.80
	3	450	947	73.94	58.98	1.94	32.88
B	4	600	952	93.80	51.67	2.41	29.31
C	5	600	950	112.24	65.38	2.86	36.98
D	6	900	951	134.44	35.68	3.39	24.86
	7	900	954	135.44	39.79	3.41	27.00
	8	900	951	134.94	38.42	3.40	26.32

Table 3 – Results of linear regression analysis

Serie	Prototype	X	Y	Regression analysis result	V_R (kN/m)	V_{ut} (kN/m)	V_R/V_{ut}	Difference (%)
A	1	3.52	409	m = 139.36 k = -0.051361	32.45	30.16	1.08	-7.59
	2	3.52	463		32.15	33.80	0.95	4.89
	3	3.52	445		32.54	32.88	0.99	1.05
B	4	2.65	312		29.76	29.31	1.02	-1.52
C	5	2.65	329		35.61	36.98	0.96	3.72
D	6	1.76	185		26.13	24.86	1.05	-5.11
	7	1.76	199		26.33	27.00	0.98	2.50
	8	1.76	195		26.33	26.32	1.00	0.36

test ultimate bending moment under the line load. The mean value for the resistant shear stress, τ_u, is equal to 0.1006 MPa, the corresponded standard deviation, σ, equal to 0.0224 MPa; consequently, the variation coefficient is then equal to 22.3 %.

The validation of the value of the mean resistant shear stress τ_u is made by the comparing each specimen ultimate resistant shear force determined with this stress with its test ultimate shear force. For the determination of each specimen ultimate resistant shear force, equation 9 must be modified into equation 10.

$$\eta . N_{cf} = N_c = \tau_u \; b.(L'+L_0) + \mu . V_{ut} \qquad (10)$$

Thus, each specimen resistant bending moment is given by equation 11.

$$M_{pR} = [\tau_u \; b.(L'+L_0) + \mu . V_{ut}] z + M_{pr} \qquad (11)$$

where the lever arm ***z*** is evaluated by the equation 7 and M_{pr} by the equation 3. In equation 3, N_c is taken according to the equation 10 and N_{pa} equal to $A_p . f_y$. The relation between this resistant moment and the resistant shear force is equal to $M_{pR} = V_{ut} . L'$. Therefore, the calculated resistant shear force can be determined by the equation 12.

$$V_{ut} = \frac{[\tau_u \; b.(L'+L_0) z + M_{pr}]}{(L' - \mu . z)} \qquad (12)$$

Table 5 presents the results of comparative analysis between the calculated resistant shear force determined according to equation 12, using the average value of resistant shear stress τ_u and friction coefficient μ equal to 0.5, with respect to the test ultimate shear force for each specimen. The analysis of the results shows that the ratio between calculated resistant shear force, $V_{UT\ calculated}$, and the test measured one, $V_{UT\ test}$, for each specimen is within the limits commonly used (between 0.85 and 1.15). This fact reveals that the calculated results are, therefore, acceptable.

A comparative analysis between the calculated values by the ***m-k*** method and partial interaction method are shown in table 6. This comparison reveals that the partial interaction method provides, for the majority of composite slabs tested herein, slightly larger values for the resistant shear force. The mean difference between the two

Table 4 – Resistant shear stress results

Series	Prototype	V_{ut} (kN)	M_{ut} (kNm)	η	τ_u (MPa)
A	1	28.63	12.6963	0.1039	0.0717
	2	32.04	14.2351	0.1524	0.1156
	3	31.14	13.8281	0.1381	0.1025
B	4	27.90	16.3286	0.1687	0.1047
C	5	35.14	20.5929	0.2342	0.1481
D	6	23.64	19.9734	0.1783	0.0789
	7	25.76	21.8630	0.2105	0.0944
	8	25.03	21.2202	0.1985	0.0885

Table 5 – Partial interaction comparative result analysis

Series	Prototype	$V_{ut\ test}$ (kN)	$V_{ut\ calculated}$ (kN)	$\frac{V_{ut\ calculated}}{V_{ut\ test}}$	Difference (%)
A	1	28.63	31.78	1.110	-10.98
	2	32.04	31.63	0.987	1.30
	3	31.14	31.74	1.019	-1.88
B	4	27.90	27.95	1.002	-0.16
C	5	35.14	32.49	0.925	7.54
D	6	23.64	26.15	1.106	-10.62
	7	25.76	26.36	1.023	-2.35
	8	25.03	26.22	1.047	-4.73

procedures is equal to 4 %, which indicates that both methods produce very similar results.

6. Concluding Remarks

The overall analysis of the test results of the composite slabs built with steel-deck MF-50 revealed that initially there is a full composite action between profiled steel sheeting and the concrete. With increasing loads, concrete cracking occurs accompanied by the breakdown in the chemical bond between the sheeting and the concrete. From this point onwards, partial interaction behavior is observed since the profiled sheeting embossments are unable to transfer the total shear stresses between the sheeting and the concrete. Consequently, there is a relative displacement or slip between them. In all cases, the failure mode was by shear bond.
Based on this failure mode, the ***m-k*** method and partial interaction method, prescribed by ABNT NBR 8800 (2008), for calculating the composite slab shear strength were analyzed. For determining the ultimate resistant shear force, the partial interaction method is an alternative to the ***m-k*** procedure especially when shear connectors or additional longitudinal reinforcing bars are used. The resistant shear forces were determined according to these two methods. The ultimate resistant shear forces calculated by both methods are very similar indicating that both procedures provide safe and reliable results.

7. Acknowledgments

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Table 6 – Resistant shear force comparative analysis

Series	Prototype	$V_{ut\ test}$ (kN)	$V_{m\text{-}k}$ (kN)	$V_{\tau u}$ (kN)	$\frac{V_{\tau u}}{Vm\text{-}k}$
A	1	28.63	30.80	31.78	1.032
	2	32.04	30.48	31.63	1.038
	3	31.14	30.81	31.74	1.030
B	4	27.90	28.33	27.95	0.987
C	5	35.14	33.83	32.49	0.960
D	6	23.64	24.85	26.15	1.052
	7	25.76	25.11	26.36	1.050
	8	25.03	24.94	26.22	1.051

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