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Moment Redistribution in Continuous Profiled Steel Sheeting

Redistribution des moments dans les tôles profilées continues

Momentenumlagerung in durchlaufenden Profilstahlblechen

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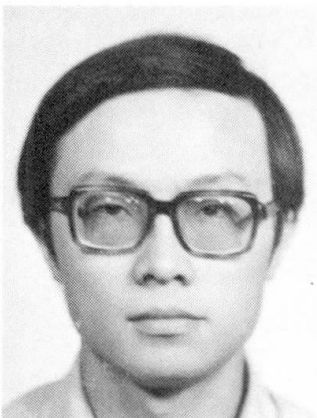
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SUMMARY

The load capacity of continuous sheeting calculated according to the ECCS European Recommendations is smaller than that obtained from testing. Understandably, manufacturers and designers prefer the use of testing rather than design. Research at EPFL has developed a simple test procedure which determines the load capacity of multispan cold-formed profiled sheeting. This procedure conservatively predicts the redistribution that occurs at interior supports.

RÉSUMÉ

La capacité portante d'une tôle profilée continue calculée à l'aide des recommandations européennes CECM est inférieure à la valeur déterminée par essai de charge. C'est pourquoi actuellement les fabricants et les ingénieurs préfèrent avoir recours aux essais plutôt qu'aux calculs. Une recherche entreprise à l'EPFL a conduit à l'établissement d'une procédure d'essais permettant de déterminer de façon précise la capacité portante d'une tôle continue, compte tenu de la redistribution du moment sur appui.

ZUSAMMENFASSUNG

Die nach den europäischen Empfehlungen EKS berechnete Traglast von Profilblechen ist kleiner als der durch Versuche ermittelte Wert. Hersteller und Ingenieure ziehen deshalb die Versuchsresultate den Berechnungen vor. An der EPFL wurde ein einfacher Test entwickelt, mit dem die Traglast von durchlaufenden Profilstahlblechen genau ermittelt werden kann. Der Momentenumlagerung über den Stützen wird dabei Rechnung getragen.

1. INTRODUCTION

The present ECCS European Recommendations for the Design of Profiled Sheeting [1] are based upon the effective width concept and empirically determined factors. The use of empirical factors is necessary in the design procedure due to difficulties in modelling :

- initial imperfections,
- residual stresses,
- elastic buckling of individual plate elements.

However, the empirical factors used in the ECCS design procedure are based upon tests which were performed on single span specimens only. Using similar factors to predict the flexural capacity of multiple span specimen yields overly conservative values. As a result, most manufacturers prefer testing to the ECCS design values when determining ultimate load capacities.

Research which better defines the reserve capacity of continuous span specimens has been conducted. The principal objectives of this research are :

- to determine the accuracy of the present ECCS design procedure,
- to compare the ultimate load capacity of similar single and multiple span specimens using a simple test procedure,
- to determine the increase in ultimate load capacity which occurs in multiple span specimens as a result of moment redistribution near interior supports.

2. EXPERIMENTAL INVESTIGATION

2.1 Test specimens

Profiled sheetings were chosen according to two criteria. Firstly, sections without embossments or intermediate stiffeners were used in order to reduce the number of assumptions necessary when calculating section properties and predicting behaviour. Secondly, profiled sheetings which have found common usage in composite cold-formed floors constructed in Switzerland were employed. As a result the following sections were chosen :

- Montana 57/0.80 mm (unsymmetric trapezoidal ribs),
- Hi-Bond 55/0.88 mm (trapezoidal ribs),
- Holorib 51/0.75 mm (dovetailed ribs).

These three sections are shown in Figure 1.

Three types of tests were performed on each sheeting; this enabled a comparison of behaviour with similar single and multiple span specimens. These tests are identified as series 1, 2 and 3. Load placement and span lengths were chosen such that test results could be directly compared with the ECCS design procedure. The coiled sheeting from which the specimens were formed was inspected both before and after the forming process. Each specimen was then marked prior to shipping. This minimised dimensional variation between test series on similar test specimens.

Test series 1 consisted of a single span simply supported profiled sheet, loaded symmetrically by two equal line loads. These tests determined the ultimate flexural strength of a single span specimen in pure bending. The static testing system for this test series is shown in Figure 2 a).

Test series 2 consisted of a single span profiled sheet, simply supported and loaded at midspan. This test series determined the influence of a concentrated load in the region of maximum moment. The line load at midspan simulates the effect of the interior support of a two span specimen . In Figure 2 b) the static system is shown.

Test series 3 consisted of a profiled sheet continuous over two equal spans. Each span length was the same as that used in test series 1. Two lines loads, of equal
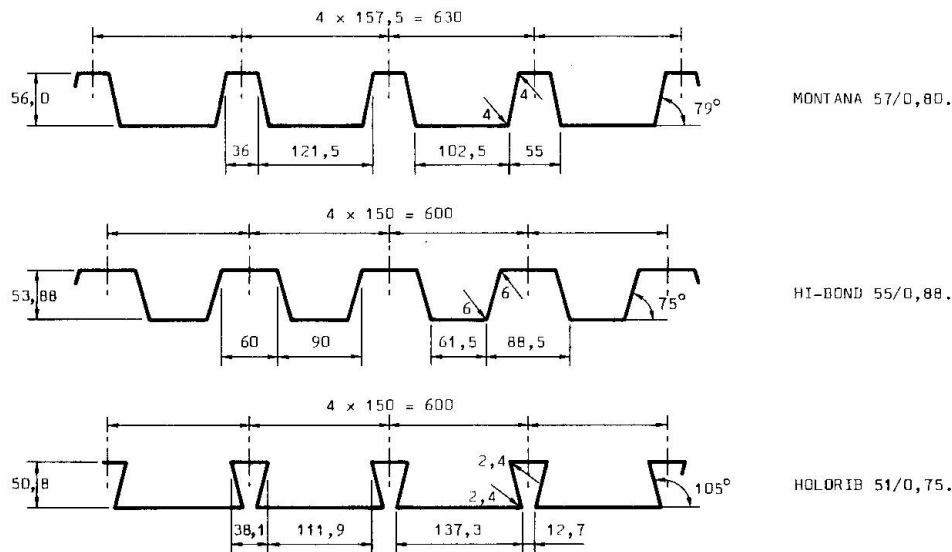
Fig. 1 : Profiled sheeting sections.

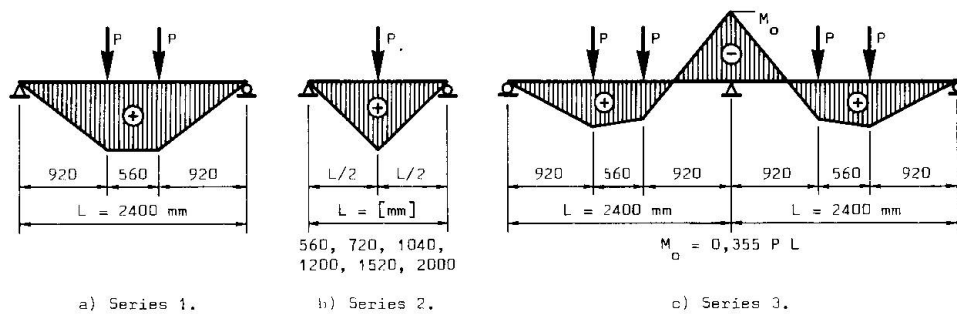a) Series 1.   b) Series 2.   c) Series 3.

Fig. 2 : Static system for the tests.

magnitude, were applied to each span at the same location as in test series 1. The static system is shown in Figure 2 c).

For each sheeting, three series 1 tests, nine series 2 tests and two series 3 tests were performed.

2.2 Test Procedure

Before testing, the cross-sectional geometries and material thicknesses of all specimens were measured. All measurements were made in accordance with the ECCS Recommendations for the testing of profiled metal sheeting [2]. Six tensile test specimens were cut from the stock material used to form each profile. After the forming process six additional specimens were cut from the centre of flat plate elements and an additional six at the curved portion between these elements. All specimens were tested according to the standard ISO procedure [3]. A more detailed review of the test procedure and the test specimens is contained in [4].

Test series 1. The procedure adopted for conducting these tests was a modification of the ECCS Recommendations [2]. The blockings, required by ECCS between all ribs under concentrated loads, were provided only at exterior ribs. This change was made for two reasons. Firstly, it is difficult to determine the distribution of the applied load on the specimen with more than two blocks and secondly, using only two blocks, it is much easier to assemble the test.

Test series 2. The ECCS Recommendations were followed for this test series. Blocking is not required as failure occurs at the location of the applied load.

Test series 3. This series resembles test series 1. However, instead of exterior blocking beneath the concentrated loads, a 150 mm length of profiled sheeting was placed between the specimen and the transverse spreader beam. This profiled sheet was the same shape and thickness as the specimens tested.

2.3 Test results

Series 1. The ultimate load of the test specimens were compared to the ultimate load calculated using the ECCS Recommendations. This comparison is shown in Table 1. A very good correlation between test results and calculated values was observed; the maximum difference between theoretical and test values of ultimate moment was 5 %.

Series 2. An interaction diagram of moment and support reaction at ultimate load, calculated using the ECCS Recommendations, is shown in Figure 3. Test results are also presented on this figure. Again, good correlation between experimental and analytical results was observed. The maximum difference between theoretical and test values of ultimate moment was 9 %, the standard deviation 4.5 %.

Series 3. Ultimate loads from these test specimens and theoretical values calculated using the ECCS procedure are presented in Table 2. The theoretical values of ultimate load do not correspond to experimental results. The maximum difference between theoretical and experimental values was 37 % and the minimum difference was 21 %. The test values of ultimate load were always larger than those predicted by the ECCS procedure. The difference between the experimental ultimate load and the ultimate load predicted by ECCS represents the reserve capacity due to moment redistribution near the interior support. The redistribution factor, α, is defined as the reserve capacity of the specimen divided by the ultimate load predicted by ECCS.

Table 1 : Test results of series 1 in kNm/specimen.

PROFILE TYPE	TEST NUMBER	STATIC SYSTEM			
		$M^+_u = 0,92\ P_u$		$M^-_u = 0,92\ P_u$	
		$M^+_{u,series1}$	$M^+_{u,ECCS}$	$M^-_{u,series1}$	$M^-_{u,ECCS}$
MONTANA 57/0,80	MO22	3,243	3,321		
	MO21			3,114	3,124
$f_y = 294\ N/mm^2$	MO23			3,197	3,085
HI-BOND 55/0,88	HI22	3,340	3,485		
	HI21			3,257	3,227
$f_y = 306\ N/mm^2$	HI23			3,243	3,163
HOLORIB 51/0,75	HO23	3,229	3,257		
	HO21			2,995	3,106
$f_y = 291\ N/mm^2$	HO22			2,967	2,969
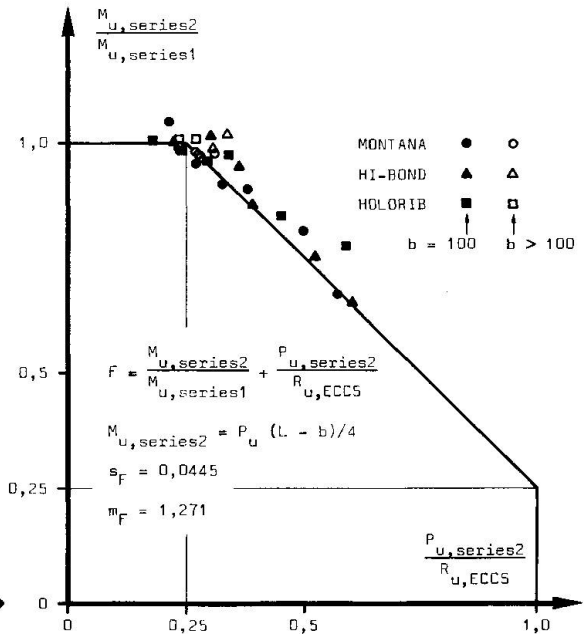
Fig. 3 : M-R interaction diagram.

PROFILE TYPE	f_y [N/mm^2]	$M^-_{u,series2}$ [kNm/specimen] [1]	$P_{u,series2}$ [kN/specimen] [2]	$P_{u,series3}$ [kN/specimen] [3]	$\alpha = \dfrac{P_{u,series3}}{P_{u,series2}} - 1$
MONTANA 57/0,80	294	2,871	3,370	4,264	0,265
HI-BOND 55/0,88	306	3,094	3,631	4,409	0,214
HOLORIB 51/0,75	291	2,868	3,366	4,623	0,373

Table 2 : Test results of series 3 and redistribution factor.

[1] The ultimate moment is given by the interaction moment-reaction diagram in series 2 test.

[2] $P_{u,series2} = M^-_{u,series2}/0,355\ L$ (elastic linear solution).

[3] Average values of tests.

3. ANALYSIS

The following analysis is used to determine the redistribution factor, α, for multiple-span cold-formed profiles using a semi-analytical procedure. Based on an elastic analysis, the compatibility equation at ultimate load for a beam with two equal spans, L, uniformly loaded, is given by :

$$\frac{M_0 \, L}{3 \, EI_0} = \frac{p_0 \, L^3}{24 \, EI_0} \tag{1}$$

M_0 : moment at the interior support of a two span continuous beam assuming linear behaviour; this is calculated using the simple beam formula and the yield stress of the material,

I_0 : moment of inertia of the entire cross section,

L : single span length, both span lengths equal,

E : modulus of elasticity,

p_0 : uniform applied load at M_0.

In equation (1), the left hand term represents the end rotation in a simply supported span due to a single end moment, M_0. The right hand term represents the end rotation in a simply supported span uniformly loaded. By equating these two components, an expression for the moment at the interior support of a two span beam is obtained. To account for the additional capacity observed during testing, equation (1) may be rewritten to include the non-linear components of rotation at the interior support. Overall plasticity does not occur in most sheeting and thus, this new expression is written as follows :

$$\frac{M_0 \, L}{3 \, EI_0} + \Delta\theta_{el} + \Delta\theta_p = \frac{p_u \, L^3}{24 \, EI_0} \tag{2}$$

$\Delta\theta_{el}$: rotation at the interior support due to local buckling of individual flat plate elements,

$\Delta\theta_p$: rotation at the interior support due to the presence of a concentrated support reaction; this rotation is permanent,

p_u : uniform applied test load at failure or predicted ultimate load.

In expression (2) the left hand terms represent three separate components of rotation. The sum of these three components equals the rotation which occurs at the interior support in a cold-formed profile. To define these three components of rotation, illustrated in Figure 4, the following assumptions are made :

- the negative moment region near the interior support of a two span uniformly loaded specimen can be modelled by a simple span beam with a concentrated load at midspan,

- the effect of concentrated load is so localised that the magnitude of $\Delta\theta_p$ is independent of span length.

A typical series 2 load-midspan deflection curve which is shown in Figure 5. Theoretically, a compact cross section with no initial imperfections will attain overall plasticity without instability taking place and therefore, complete moment redistribution. This behaviour is identified by curve OAB. In reality, both initial imperfections and local buckling cause failure at a lower applied load than that predicted by OAB. Curve OKN represents this behaviour. When a concentrated load is present at the same location as the maximum moment, a further reduction in capacity is observed due to web crippling. This is shown by curve OEF. As loading is increased, four different types of behaviour are predicted by curve OEF. In the first region, OC, linear behaviour prior to local buckling is observed. In region CD nonlinearity, primarily caused by local buckling in the different flat plate elements of the specimen, is observed. In region DE, the effects of the concentrated load dominate behaviour. At point E, failure of the entire section occurs. Curve GJF is typical of the post-elastic failure behaviour of cold-formed sheet-
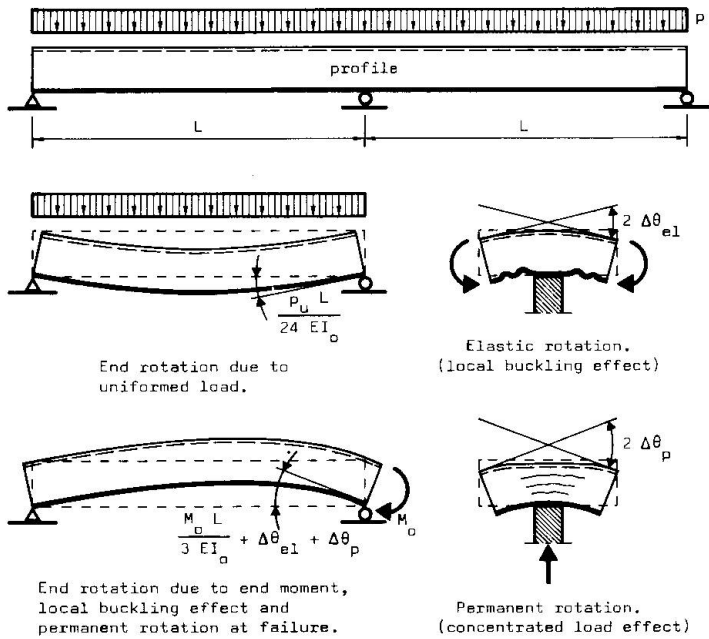
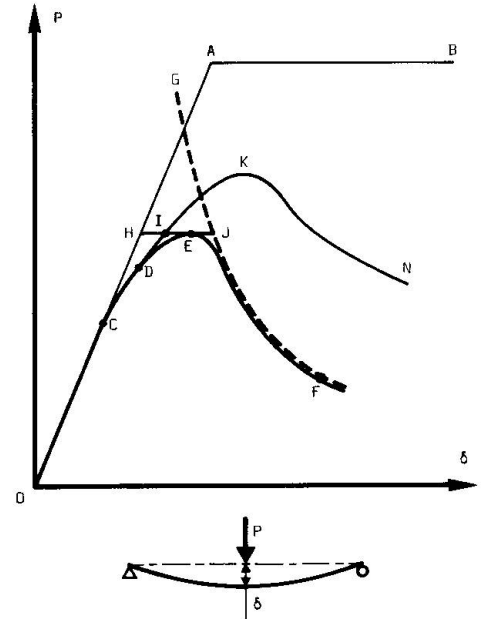Fig. 4 : Components of compatibility equation (2).

Fig. 5 : Typical load-midspan deflection curve.

ing. The nature of this curve has been investigated by several researchers [5] [6] [7]. Schardt [7], for example, has used a straight line. Unfortunately, this curve is difficult to obtain by theoretical means for cold-formed sheeting.

To obtain $\Delta\theta_{el}$ and $\Delta\theta_p$ the following procedure is proposed : rotation due to buckling of individual plate elements is dependent upon moment gradient, span length, and the moment-curvature relationship. Using the moment-curvature relationship from test series 1 and a finite difference model, $\Delta\theta_{el}$ can be plotted as a function of span length, for each sheeting. The magnitude of this component of rotation on the midspan deflection of test series 2 is shown in Figure 5 as HI. Rotation due to support reaction is localised and independent of span length. Thus, $\Delta\theta_p$ is determined by the nonlinear rotations taken from testing; provided that the span length is sufficiently short to insure elastic local buckling of the flanges does not occur. For the sections tested, this length is less than ten times the depth of the section. Component HI approaches zero and the remaining nonlinear component of midspan deflection, for test series 2, is represented by IJ in Figure 5.

Using this procedure two different tests obtain the two components of rotation, $\Delta\theta_{el}$ and $\Delta\theta_p$. These rotations are used to compute the ultimate load capacity of multispan profiled sheeting. The first test, series 1, establishes the moment curvature characteristics of the section subject to bending moment alone. The second test, a small span with a single concentrated load, determines the effects of concentrated reaction. The non-linear components of rotation at the interior support can thus be expressed as :

$$\Delta\theta_{el} + \Delta\theta_p = \alpha \frac{p_0 L^3}{24 EI_0}$$

(3)

Using equations (1) and (2) the ultimate load capacity, p_u, is expressed as :

$$p_u = (1 + \alpha) p_0$$

(4)

Values of α have been calculated using this procedure for the sections tested. These values are compared to the experimentally determined redistribution factors

and are listed in Table 3. Good agreement between observed and predicted redistribution was obtained, the average difference being 14 %.

PROFILE TYPE	$I_0 \cdot 10^6$ [mm^4/specimen]	$\Delta\theta_{el} \cdot 10^{-3}$ [rad]	$\Delta\theta_p \cdot 10^{-3}$ [rad] 1)	α_{cal} a)	α_{test}
MONTANA 57/0,80	0,386	3,31	3,75	0,228	0,265
HI-BOND 55/0,88	0,389	2,62	3,90	0,205	0,214
HOLORIB 51/0,75	0,420	3,72	3,93	0,284	0,373

Table 3 : Comparison of the tested and calculated redistribution factor.

1) $\Delta\theta_p$ is obtained from a 560 mm span series 2 test.

a) Calculated from equation (3).

4. DISCUSSION

The differences in reserve capacity, shown in Table 3, between predicted and test values of α, are due to several factors. However, it is presently believed that there are two components which account for the majority of these differences. Firstly, the deformation of the sheeting at the interior supports of a multispan specimen is larger than that observed under the concentrated load of test series 2. Secondly, even though the same sheeting was used for test series 1, 2 and 3, dimensional differences between specimens exist. M_0, however, was calculated using the measured section properties of the sheeting used in test series 1. This difference in section properties will always be present due to the flexible nature of these specimens.

To improve this procedure, theoretical work is now being conducted in two areas. These areas are the definition of the post elastic behaviour of profiled sheeting (curve GJF) and an improved model of web crippling. In addition, future testing is planned to better define the accuracy of this method.

5. CONCLUSIONS

The following conclusions are based upon an analysis of the test results presented in this paper :

1.- Variations between measured and nominal dimensions for profiled sheeting can be substantial. Actual section dimensions should be used when analyzing test data.

2.- The present ECCS Recommendations predict successfully the ultimate load capacity of single span cold formed sheeting.

3.- The ECCS procedure under-estimated the ultimate load capacity of continuous profiled sheeting by 21 to 37 %.

4.- The semi-empirical procedure outlined in this paper may be used to conservatively predict ultimate loads on multi-span profiled sheeting.

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