FAILURE MECHANISMS OF CURVED TRAPEZOILDAL STEEL SHEETING

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INTRODUCTION

Cold-formed curved steel sheets were first used to protect some parts of buildings from external agents (i.e. corner roofs, parking columns). Since a few decades ego, steel sheeting manufacturers have produced a new application: cold-formed self carrying arches (*Fig. 1*). Generally speaking, nowadays two main types of cold-formed curved profiles can be found in the market: (i) The first type consists of ribbed sheets bent to an arch (*Fig. 2*). The span of these arches commonly ranges from four to eight meters. The present investigation is focused on arches of this type bent by press-forming. (ii) The second type is obtained by folding a flat steel sheet to form a large rib (usually a large omega) and, afterwards, press-forming it into a curved shape. The spans of the arches produced this way range from 20 to 30 m.

Fig. 1. Curved sheets in an industrial hall.

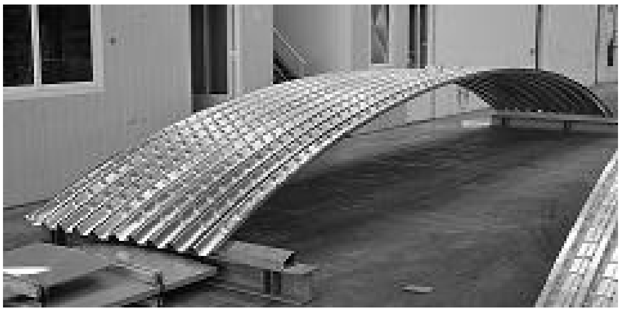


Fig. 2. Arch manufactured from a ribbed sheet.

The press-forming process introduces a large number of transverse corrugations that modifies the load bearing capacity of the original sheet. As a consequence, the effective properties of the flat profile cannot be used to design the arches. The main problem is to know how the effect of these corrugations should be taken into account. Currently, there is not any design code giving guidelines on this subject. Furthermore, there is neither a generally accepted calculation method for the corrugated sheets, nor a standardized experimental test procedure from which to obtain their effective properties or their strength. This is a problem because it has been demonstrated that under certain circumstances it can be dangerous not to consider the effects of the corrugations (see, for instance, reference [1]).

The number of scientific publications on the subject is not large. Only two investigations can be found on the first type of arches. The first one, that was written by the authors [2], presents a calculation procedure that consists of two main steps: in the first step, the effective properties of the sheet with corrugations are determined from finite element reduced models; afterwards, in the second step, the load bearing capacity of the curved sheet is calculated from 2D beam Finite Element Analyses. The cross-section properties previously determined are used in these beam analyses. The results of the proposed method showed good agreement with the results of experimental tests. The second investigation [3] also presents 2D FEM and 3D FEM analyses and experimental tests, but the results are not so satisfactory. Additional work is being performed to improve them.

There are a few more investigations related to the second type of arches. They can be classified as follows: (i) In [4] and [5], the ultimate strength of the arches is determined on the basis of experimental tests on specimens subjected to compression and bending. (ii) [6] and [7] combine analytical and experimental tests. Results of tests on arches subjected to uniform and non uniform compression are compared to the results of FEM models in [6]; while in [7], arches that span 22 m and 30 m are submitted to different kind of loads, and their behaviour is compared to that observed in FEM models generated taking into account the orthotropic nature of the curved sheet. (iii) Finally, additional theoretical investigations related to the orthotropic behaviour of the arches are conducted in [1], [8] and [9] with very interesting observations and results.

Finally, it is also worth including in this short review references [10] and [11], where members with transverse stiffeners and curved sheets with transverse corrugations are presented as new developments in the field of cold-formed structures.

The present paper shows the first steps of an investigation on the effect of transverse corrugations on the behaviour and strength of ribbed sheets. The content is mainly focused on the finite element modelling of the corrugated sheets. Two different modelling procedures are shown: in the first one, a conventional shell finite element model with initial geometric imperfections is used; while in the second, the model is generated by simulation of the press-forming process. The results of the Finite Element Analyses are compared to experimental results, paying special attention to the plastic mechanisms observed.

1 EXPERIMENTAL TESTS

Three different curved sheets were tested: H30, H40 and H55. *Table 1* and *Fig. 3* show the main geometric and material properties of the specimens.

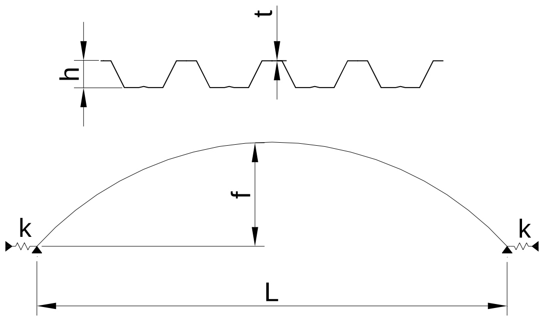


Fig. 3. Geometric parameters of the sheet.

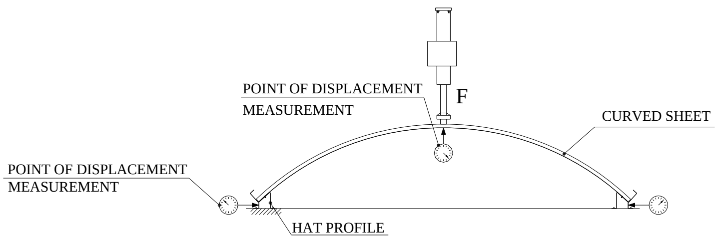


Fig. 4. Test arrangement.

Table 1. Properties of the sheets and experimental results

Cross-section	h (mm)	t (mm)	L (mm)	f (mm)	fy (N/mm^2)	Experimental ultimate load (N/m)	Proposed method (N/m)
H30-1	30	0.58	5900	510	347	600	549
H30-2	30	0.58	5900	503	347	1900	1969
H40	40	0.57	5860	598	391	2440	2460
H55	55	0.78	7500	790	360	3948	5087

The test setup is shown in *Fig. 4*. It can be observed that the curved sheets are connected to a concrete slab through two auxiliary hat profiles. The two end sections of the H30-2, H40 and H55 sheets are connected to the floor, while only one end section of H30-1 is connected to it. This arch is considered to have one sliding horizontal support. The load is applied at midspan in all tests.

The arches failed due to yielding of the cross-sections located near to the point of load application. The failure mode is presented in *Fig. 5*, where two different plastic mechanisms can be seen: the local plastic mechanism of the corrugated zone (type A mechanism); and the local plastic mechanism of the flat zone (type B mechanism). The first one is the most commonly observed. *Table 1* shows the ultimate loads obtained in the tests.

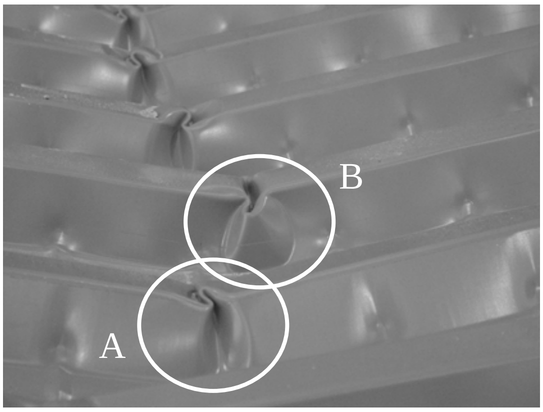


Fig. 5. Plastic mechanisms observed in H55.

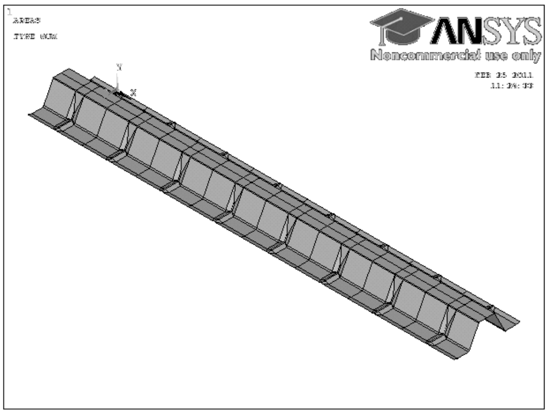


Fig. 6. Geometry of a reduced finite element model.

2 ANALYSIS OF CORRUGATED SHEETS WITH REDUCED FINITE ELEMENT MODELS

The first step of the investigation was to carry out finite element analyses on short models that included a few transverse corrugations. The ANSYS package was used to perform the analyses with the SHELL 181 finite element. As it can be observed in *Fig. 4*, the models are actually very simple. For instance, although transverse corrugations are included, the model of the sheet is not curved. The main goal was to evaluate the effect of the corrugations on the load bearing capacity of the sheet cross-section, and not to investigate the behaviour of a whole arch.

One longitudinal rib with symmetry boundary conditions at both lateral edges is considered. The model is simply supported at the ends. Two different loadings are investigated: bending and pure compression. Geometric and material nonlinearities (bilinear stress-strain curve) are taken into account in the analyses, which are solved applying the Riks method.

Only local geometric imperfections are introduced to the models. The residual stresses and the yield stress increase that result from the forming process are not taken into account.

The first analyses were performed on a model without transverse corrugations. They were carried out several times with different imperfection magnitudes. The shape of the imperfection was the shape of the first local buckling mode. The same plastic mechanism was obtained for all the imperfections considered. *Fig. 7* shows the failure of a H55 sheet subjected to bending. The resultant mechanism is similar to the type B observed in Fig 5. On the other hand, *Table 2* shows the ultimate loads obtained in the analyses. As expected, their value depends on the magnitude of the imperfection.

Afterwards, transverse corrugations were introduced to the models. It should be pointed out that their geometry was measured approximately on the specimens tested. The analyses were carried out in a similar way as the previous analyses on sheets without corrugations. This time, however, a significant dependence of the failure mechanism on the initial imperfection shape was observed. If no imperfection is introduced, or if the upper flange at the corrugation is initially bowed downwards, the failure mechanism obtained is not correct. Actually, the result is the type B mechanism. To obtain the correct mechanism, type A, the flange at the corrugation should be initially bowed up. The plastic mechanism that results from the analyses is shown in *Fig. 8*. Yield lines are localized in a small zone of the upper flange, as occurs in the experiments (*Fig. 5*).

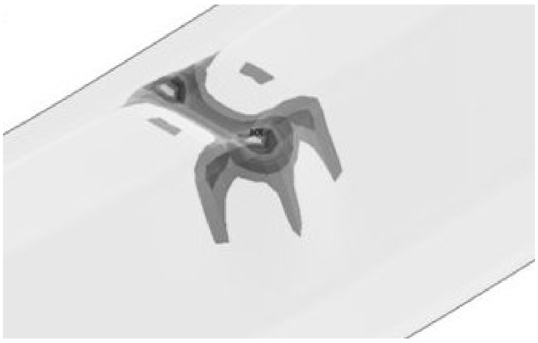


Fig. 7. Plastic strains in a sheet without corrugations after limit point.

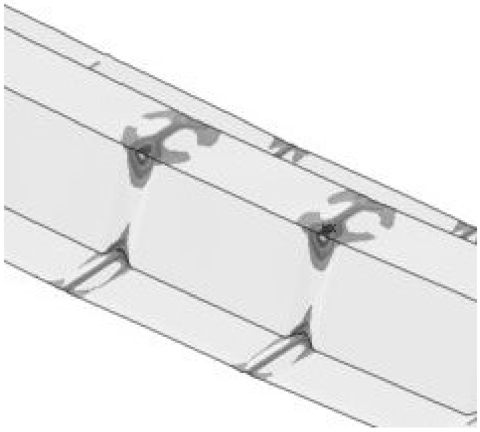


Fig. 8. Plastic strains in a sheet with corrugations after limit point.

Table 2. FEM ultimate loads for H55 (calculated with nominal material properties)

Imperfection (mm)	Compression (N per rib)		Bending (N per rib)	
	Without corrugations	With corrugations	Without corrugations	With corrugations
0.1	35136	18559	2882	1591
0.25	33661	17987	2695	1538
0.5	31816	16176	2523	1503
1	28989	15182	2287	1445

Table 2 also contains the ultimate loads that result from these analyses. These loads are rather lower than the values previously obtained for the plain sheets. In view of these results, it can be concluded that transverse corrugations can significantly decrease the load bearing capacity of a ribbed sheet.
Finally, it is worth mentioning that the reduced models shown in this section were used to predict the strength of the tested sheets. A calculation procedure, presented in the above mentioned reference [2], was developed on the basis of these reduced models. It was just an approximate procedure that resulted in rather good results for all tested specimens, but for H55 (see last column of *Table 1*). The problem with H55 was that a premature failure of the hat profiles at the floor connections provoked a significant decrease in the load bearing capacity of the arch.

3 FINITE ELEMENT MODELING OF THE FORMING PROCESS

An accurate measurement of the corrugation geometry, which is a very difficult task, is needed to improve the models shown in the previous section. It is also rather difficult to reproduce their actual shape in any standard modelling software. These are the reasons why an investigation on the simulation of the press-forming process of the corrugation was initiated. The simulation of this process will allow not only to accurately capture the shape of the corrugation, but also to obtain the residual stresses and the effects of strain hardening developed in the corrugated zone.
Presently, the initial stages of the investigation have only been carried out. The goal for the future is to link the simulation of the forming process to the simulation of the loading of the curved sheet. This will permit to investigate more accurately how corrugations change the behaviour of the sheets, including all the effects of the forming process. Another advantage of this procedure is that it will allow to easily analyze sheets with different size of corrugations.
Fig. 9 shows the geometric model considered in the analyses. It consists of three main parts: the flat ribbed sheet, the die and the punch. To reduce the computational cost, symmetry boundary conditions are applied to model only half corrugation. Nowadays, analyses have been performed only on H55 profile.

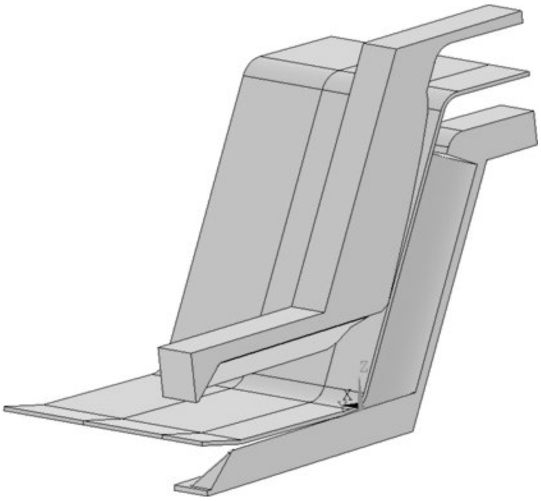


Fig. 9. Model of the forming process.

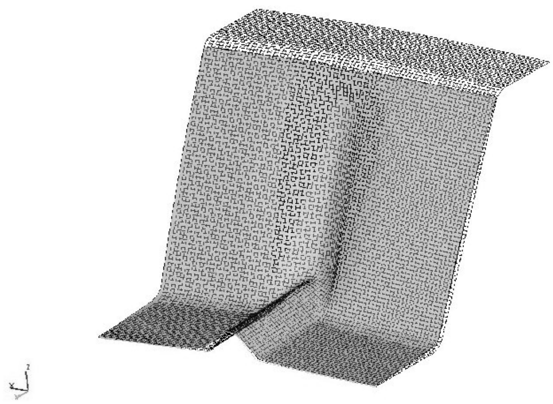
The election between solid or shell finite elements is the starting point. Here, analyses are carried out with ANSYS SOLID 95 and ANSYS SHELL 281 finite elements. The first one has 20 nodes and 14 integration points per element. The second has 8 nodes, 9 integration points on its surfaces, and 3 integration points in the thickness (when yield is reached the number integration points in thickness change to 5).

A trilinear elastic-plastic curve with isotropic hardening is used to model the material. This curve was determined from tensile tests on coupons extracted from the flat parts of the tested sheets.

In relation to the boundary conditions, it should be pointed out that: (i) vertical displacements are imposed to the nodes of the punch and die (negative and positive, respectively), all their other degrees of freedom are constraint; (ii) symmetry boundary conditions are applied to the longitudinal edges of the sheet and to the lines at the corrugation; (iii) the vertical displacement of the sheet is constrained with a spring of small rigidity connected to one of the corner nodes to avoid rigid body motion. Contact elements are placed between sheet, punch and die. The selected contact algorithm is the augmented lagrangian method.

An implicit solution method is used to carry out the displacement imposed analysis. This analysis is performed in two steps: loading (forming) and springback.

In *Figs. 10* and *11*, the results of the analyses are verified by comparing the resultant geometry to the actual geometry of the corrugation, which have been previously captured by means of a 3D laser scanner.



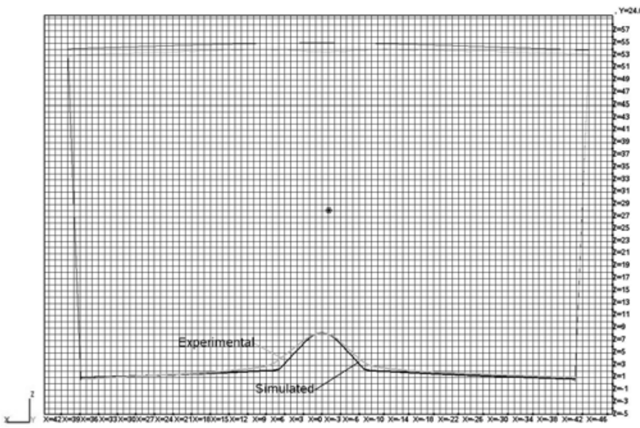


Fig. 10. FEM vs actual corrugation (3D view). *Fig. 11.* FEM vs actual corrugation (2D view).

At the moment of writing the present paper, the authors are still working on the simulation of the press-forming process to improve the results obtained, and to reduce as much as possible its computational cost. In spite of this, some preliminary remarks can be done on the basis of the work carried out so far: (i) The results concerning geometry are acceptable (see *Figs. 10* and *11*), and will be improved in the near future. (ii) Acceptable results in relation to final strains are also obtained. For instance, the ultimate strain limit of the steel is not reached. (iii) As expected, shell finite elements are much faster than solid finite elements (about 15 % faster). (iv) However, it cannot be currently stated that solid and shell analyses lead to the same results. Further investigation is needed to clarify this point.

4 CONCLUSIONS

It could be thought that transverse corrugations in cold-formed arches curved by press-forming would act as stiffeners and would, consequently, improve their performance. The results of the Finite Element Analyses carried out in the present investigation demonstrate that this is not true. It has been observed that corrugations can significantly reduce the load bearing capacity of the original ribbed sheets. This confirms what was observed in previous investigations where the experimental ultimate load of a curved sheet subjected only to bending (H30-1 test in *Table 1*) was compared to the ultimate load of a flat sheet.

However, it is underlined that the finite element models applied herein to obtain these results are very simple. They do not take into account all the effects of the press-forming process, and it is difficult to capture the actual behaviour of the corrugated sheet from them. Future investigations on the press-forming simulation process, together with subsequent analyses of the loading process, will shed some light on the reasons why corrugations decrease the strength of curved sheets.

The authors would like to express their thanks to METALPERFIL S.A. for helping with the experimental tests.

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