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BEHAVIOUR OF EXPANDED METAL PANELS UNDER SHEAR LOADING

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Abstract. *Experimental and theoretical study of expanded metal panels (EMP) has shown that they are useful for seismically retrofitting reinforced concrete moment resisting frames (RC-MRF). Although this product has merit of strength and ductility, it is at present only used for non-structural applications. There is no guidance existing to help the engineers determine the mechanical properties or to indicate in which field of the structures this product can be used. With the aims at providing quantitative data for these purposes and at introducing a simplified model of EMP working in shear, description and comparison of the results of 22 monotonic and cyclic experiments of 4 profiles of EMP in small and large scale is presented. Numerical approach with FINELG, a nonlinear finite element code developed at University of Liege, is used to calibrate and simulate the tests. A good correlation between tests and numerical simulations is observed.*

1 INTRODUCTION AND REVIEW OF PREVIOUS RESEARCH

EMP is a truss made from metal sheet by cuttings, cold-stretching and flattening [1]. Cuttings and cold-stretching make a metal sheet become a three-dimension structure. It becomes a two-dimension sheet by flattening. An expanded metal (EM) sheet – Figure 1 – has many rhomb-shape stitches, each with four bars having the same dimensions. It is characterized by four dimensions – LD, CD (the diagonals), A (the width), and B (the thickness of the bars). These dimensions are illustrated in Figure 2.

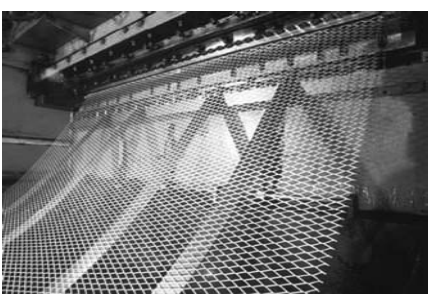

Figure 1 – Fabrication of expanded metal sheets

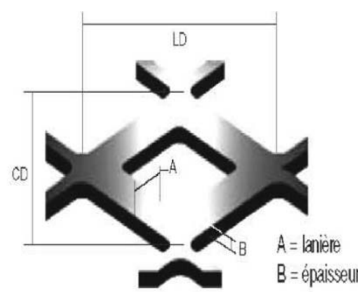

Figure 2 – An expanded metal rhomb-shape stitch

There are two types of the EM product: normal (or standard) and flattened types. In the normal type, rhomb-shape stitches are connected together with overlaps at the end of each bar. In contrast, there is no overlap between stitches in flattened type. They are continuously connected together to form a completely flattened sheet. At the moment, EM is mainly used for filters, in electrical applications or for the protection of machines (worker's safety) or anti-intrusion fences for buildings…etc. Because there are no calculation and mechanical criteria for these types of material, it is seldom used in structural applications [1], [2]. In the stages 2005-2008 of the MacroMousses Project, a research work was done by Etienne PECQUET at University of Liege. It aimed to determine the mechanical behaviour of small scale EMP under monotonic shear loading. First, mechanical properties of an EM bar were determined from tensile tests. After that, analytical models, using in-plane and extended-plate theory and numerical simulations, were used to characterize small scale EMP in small scale (biggest dimensions being equal to 1000mm) under monotonic shear loading. From PECQUET's results, one can deduce that the EMP works with one tension band developed in post-buckled stages. However, there is some more information needed to take into account when modelling EMP as working in seismic situations: First, because the thickness of bars is very small in comparison to the dimension of the sheet, the EMP is always globally buckled under a rather low shear force. Due to that, it is necessary to assess the contributions of the compressive band of EMP before globally buckling to the overall resistance of EMP. Second, numerical simulations should be performed not only in small scale dimensions of EMP. Third, in the seismic context, models of EMP under monotonic shear loading may not cover for seismic cyclic loads. Therefore the simulations of the behaviour of EMP should be calibrated on both small and large scale tests of EMP subjected to monotonic and cyclic shear loading.

2 DESIGN OF EXPERIMENTS

There are three stages of tests: (1) tests to determine mechanical properties of EMP material; (2) tests of small scale panels and (3) tests of large scale panels. The tests should set forward which one, among two types of EMP, is the most suitable for structural applications to address the global hysteretic behaviour of EMP under shear loading. Moreover, how to connect test frame with EMP should be taken into account. The effectiveness of connections will influence on the practical use of EMP. Figure 3 and 4 show the views of tests in small and large scales respectively.

Figure 3 – Global view of small scale tests

Figure 4 – Global view of tests in large scale

3 DETAILS OF SPECIMENTS

Four profiles of EM are studied experimentally. Details of all testing specimens are given in Table 1 and 2. It is worth noting that weld and glue epoxy connections are used in 22 small scale tests, and only weld connections are used in large scale tests. In addition, in small scale tests, there are two possibilities of erecting EMP to the test frame corresponding to two directions of EMP noted by 'sens1' and 'sens2' in Table 1. This is graphically explained in Figure 5.

Table 1 – Details of all testing small scale specimens

Specimens	LD(mm)	CD(mm)	A(mm)	B(mm)	EM type	Type of tests	Sens
1	51	27	3,5	3,0	Flatten	1-Mono 2-Cyclic	1
2	51	27	35	30	Flatten	1-Mono 2-Cyclic	2
3	86	46	43	30	Flatten	1-Mono 2-Cyclic	1
4	86	46	43	30	Flatten	1-Mono 2-Cyclic	2
5	51	23	32	30	Normal	1-Mono 2-Cyclic	1
6	51	23	32	30	Normal	1-Mono 2-Cyclic	2
7	86	40	32	30	Normal	1-Mono 2-Cyclic	1
8	86	40	32	30	Normal	1-Mono 2-Cyclic	2

Figure 5 – Two possibilities of erecting EMP to the testing frames (left: sens1; right: sens2)

Table 2 – Details of all testing large scale specimens (in mm)

Specimens	LD	CD	A	B	Type of EM	Type of tests	Dimensions
1	51	27	3,5	3,0	Flatten	Monotonic	2590x2630
2	86	46	4,3	3,0	Flatten	Monotonic	2590x2630
3	51	27	3,5	3,0	Flatten	Cyclic	2590x2630
4	86	46	4,3	3,0	Flatten	Cyclic	2590x2630

4 TEST PROCEDURES

All tests are made according to ECCS – 1986 [3]. There are two stages. The first one is a monotonic test used to define the parameters of the cyclic tests, and the second one is to test EMS specimens in cyclic loading.

5 EXPERIMENTAL OBSERVATIONS

5.1 Monotonic Test

Under monotonic loading the behaviour of specimens can be divided into an elastic stage and a plastic stage. The elastic range starts from the beginning of tests until reaching yield displacement. These yield deformations range from 0,12% drift to 0,18% drift in small scale and from 0,9% to 0,99% in large scale tests. In plastic ranges, the section area of bars reduces and the slope of force-displacement curves decreases corresponding to the degradation of the stiffness. In small scale tests, there are four couples of tested EMP. In a couple, the EM profile is the same, but the erecting direction is different as in Figure 5. Because of this difference, yield displacements, yield forces, ultimate displacements and ultimate forces of each specimen are slightly different. In all the specimens, there are some discrete positions having visible out-of-plane deformations. They are different from one to others, and become clearer after rather low shear forces are applied. The buckling shapes, as shown in Figure 6, are the same for all tested EMP. There is no buckle of individual bar observed from the beginning to the end of the test. The first broken bars observed in all tests are located at the diagonal corners opposite to the force application points of the testing frame. Although some bars are broken, the sheets keep carrying shear forces. After each bar is broken the force is suddenly reduced and then increased until the EMP is completely broken. There is no failure at the connections observed in all tests. Small scale tests showed that the normal type buckles under low forces than the flattened type. In each EM type, the ultimate forces are proportional to the section area of bars and inversely proportional to the voids of the sheets. The initial stiffness of normal types is much lower than that of flattened types. Although ultimate forces in normal type specimens are less than those in flattened types, the corresponding displacements in normal types are much greater than that in flattened types. Figure 7 and 8 show the force-drift in small and large scale tests.Table 3 and 4 show the results in both small and large scale tests.

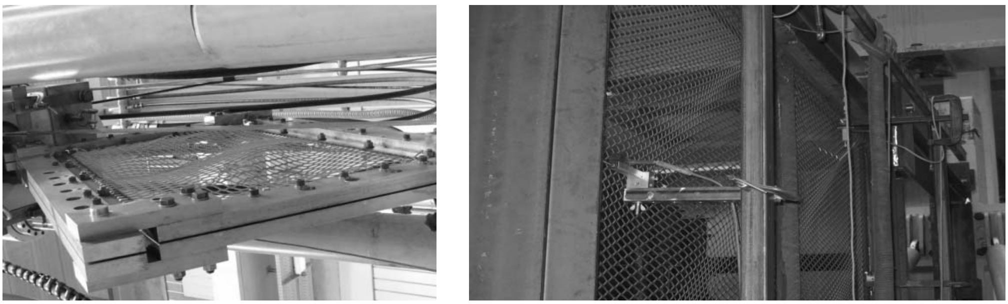

Figure 6 – Global buckling of specimens – small and large scale tests

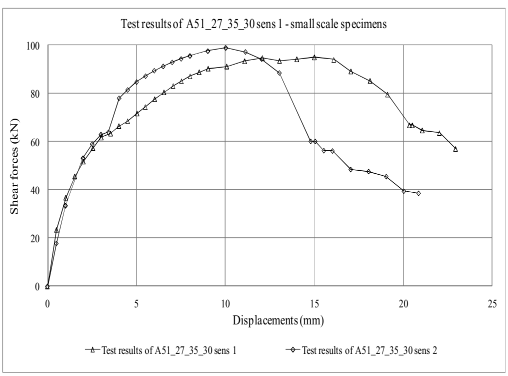

Figure 7 – Force–drift curve in monotonic tests and analytical models – small scale specimens

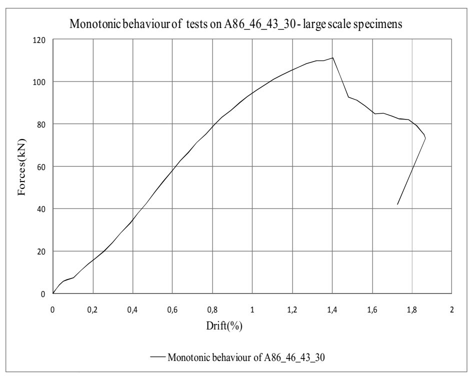

Figure 8 – Force–drift curves in monotonic tests – large scale specimens

Table 3 – Monotonic test results in large scale

Specimens	Yield force(KN)	Yield Displ. (mm)	Yield Drift (%)	Ultimate force (KN)	Ultimate Displ.(mm)	Ultimate Drift (%)
1	140	23	0,9	190,4	47,8	1,9
2	90	23,6	0,99	111,1	35,3	1,5

Table 4 – Monotonic test results – Small scale

Specimens	Yield force (KN)	Yield Displ.(mm)	Yield Drift (%)	Ultimate shear force (KN)	Ultimate Disp.(mm)	Ultimate Drift (%)
1	33,4	1,0	0,14	78,9	9,4	1,35
2	32,2	1,0	0,14	83,7	8,7	1,25
3	27,9	0,85	0,12	60,8	7,1	1,02
4	25,9	1,17	0,17	65,0	8,3	1,2
5	27,3	1,3	0,18	60,6	25,7	3,7
6	18,0	0,9	0,13	57,5	20,3	2,9
7	9,3	0,93	0,13	31,3	15,6	2,24
8	10,2	0,93	0,13	32,3	15,7	2,26

5.2 Cyclic Tests

All specimens behave elastically until reaching yield displacements, nearly the same as in monotonic tests. In the elastic range, the behaviour of all specimens is not symmetric. When the displacements become larger the hysteric loops are more symmetric. Initial out of plane deformations are clearly observed in all specimens before testing. In some specimens, this becomes much clearer after low shear forces are applied. Like in monotonic tests, all first broken bars, as shown in Figure 9 and 10, are located at four corners of the testing frame and before being broken their section areas are considerably reduced. The crack directions start at four corners and then progress to the centre of the sheets to form four crack lines. In most cyclic tests, the maximum shear force is attained on the cycle on which the first broken bars have appeared. During the first four cycles, the behaviour of the EMP is linear. From fifth cycle to the end of the tests, the force – displacement loops have stable S-shapes, characterized by a strong pinching due to the global instabilities of the EMP, which cause large degradation in stiffness of the sheets. Like in monotonic tests, tension bands are developed in every cycle. At force reversal before redeveloping new tension bands, the stiffness of the sheets is approximately equal to zero in the opposite diagonal. From the beginning to the end of the tests, there has been no failure at the connections.

Table 5 – First four cycle results – small scale specimens

Specimens	Yield forces		Yield displacements		Yield drifts	
	Monotonic	Cyclic	Monotonic	Cyclic	Monotonic	Cyclic
1	33.4	30.4	1.0	1.01	0.14	0.15
2	32.2	31.1	1.0	1.02	0.14	0.15
3	27.9	20.2	0.85	0.88	0.12	0.13
4	25.9	24	1.17	1.10	0.17	0.15
5	27.3	23.4	1.3	1.01	0.18	0.15
6	18.0	19.0	0.9	1.00	0.13	0.15
7	9.3	10.1	0.93	1.20	0.13	0.17
8	10.2	11.0	0.93	1.29	0.13	0.19

Table 5 to 7 present the results of the tests in small scale. Hysteretic behaviour of EMP is shown in Figure 11 and 12. As shown in Table 5, yield parameters of flattened type specimens in the monotonic stage are approximately equal to that in the cyclic stage. This is not true for normal types, especially when the voids of EMP are large (specimens 7 and 8). In addition, the number of cycles in hysteretic behaviour of flattened expanded metal types is greater than that of normal types as presented in Table 6 and 7. It is also observed that out of plane deformations at failure of normal type specimens are much greater than those of flattened specimens, and pinching effects on the hysteretic behaviour are much larger for normal type specimens than for flattened type specimens. Table 8 to 10 show the results in large scale tests.

Table 6 – Cyclic testing results in comparison with in monotonic tests of small scale specimens

Specimens	Ultimate forces		Ultimate		Ultimate drifts		Number of cycles(cycles)
	Monotonic	Cyclic	Monotonic	Cyclic	Monotonic	Cyclic	
1	78,9	56,0	9,4	9,8	1,35	1.41	23
2	83,7	74,0	8,7	9,7	1,25	1,40	14
3	60,8	42,5	7,1	8,7	1,02	1,30	20
4	65,0	43,3	8,3	9,3	1,2	1,34	11
5	60,6	15,5	25,7	20,9	3,7	3,0	32
6	57,5	40,5	20,3	20,4	2,9	3,0	12
7	31,3	23,2	15,6	14,5	2,24	2,1	11
8	32,3	28,9	15,7	14,5	2,26	2,1	14

Table 7 – Maximum shear forces in cyclic tests and corresponding displacements – small scale specimens

Specimens	Cyclic ultimate shear	Cyclic corresponding	Cyclic corresponding	Number of
1	71,6	8,3	1,2	20
2	-75,6	-16,9	2,4	16
3	-48,2	-20,2	2,9	26
4	-49,3	-14,8	2,1	13
5	-48	-7,3	1,1	14
6	-45	-7	1,0	10
7	27	9,3	1,33	8
8	-28	-10,8	1,56	12

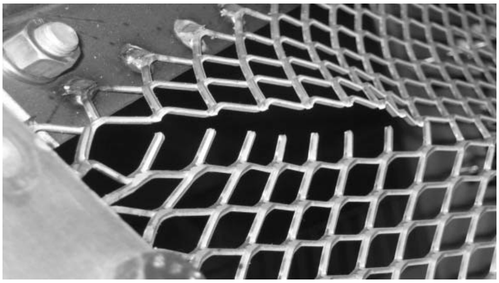

Figure 9 – Crack line and broken bars in small scale

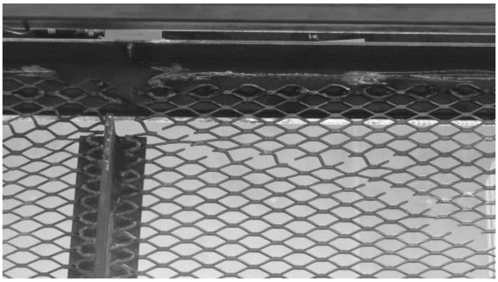

Figure 10 – Crack line and broken bars in large scale

Table 8 – First four cycle results of specimens with welded connections – large scale specimens

Specimens	Monotonic yield force (KN)	Monotonic yield Disp.(mm)	Monotonic yield Drift (%)	Forces at yielding(KN)	Displacements at yielding (mm)	Drift at yielding cycle (%)
3	140	23	0,9	140,7	22,4	0,89
4	90	23,6	0,99	93,4	23,1	0,97

Table 9 – Cyclic testing results in comparison with in monotonic tests of large scale specimens

Specimens	Ultimate forces		Ultimate displacements		Ultimate drifts		Number of cycles(cycles)
	Monotonic	Cyclic	Monotonic	Cyclic	Monotonic	Cyclic	
3	190,4	195	47,8	42,4	1,9	1,8	8
4	111,1	109	35,3	35,4	1,5	1,51	8

Table 10 – Maximum shear forces in cyclic tests and corresponding displacements – large scale

Specimens	Cyclic ultimate shear forces (KN)	Cyclic corresponding displacements (mm)	Cyclic corresponding drifts (%)	Number of cycles (cycles)
1	195	42,4	1,8	8
2	109	35,4	1,51	8

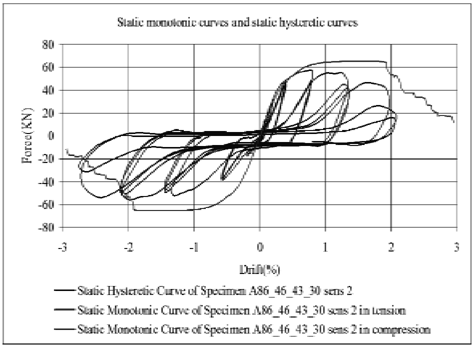

Figure 11 – Hysteretic behaviour of flattened type specimens – welded connections – small scale tests

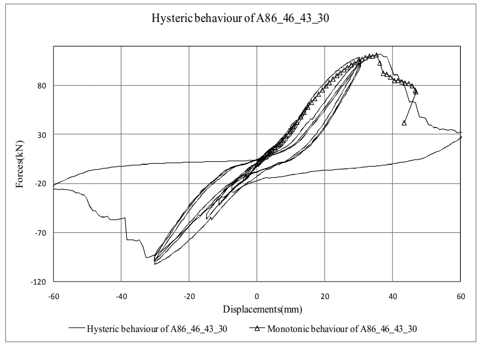

Figure 12 – Hysteretic behaviour in large scale tests

6 SUMMARY OF OBSERVATIONS

An experimental test program has been carried out on small scale and large scale of un-stiffened EMP. The correlation between the analytical model and monotonic tests is not constant. It may be that a simple tension band does not represent correctly the monotonic behaviour of the sheets. Because under rather low shear forces the sheets are globally buckled, the contribution of compression diagonal to the resistance of sheets can be neglected. The hysteretic loops of all specimens are S-shaped due to pinching effects, but they are stable. The displacement ductility of all specimens is largely different, ranging from 10 to 20. Pinching effects on all specimens caused the degradation of stiffness of the sheets. This results in a smaller enclosed area under the hysteretic curve and, therefore, a lower amount of energy absorbed by the system during successive cycles. The deflection required to redevelop the tension field correspond to the yielding displacements experienced by the sheets on the previous cycles. In both monotonic and cyclic phases of the tests, all sheets buckle at very low shear forces. Some specimens are globally buckled before testing. Furthermore it is observed that normal types of small EMP specimens buckle more easily than flattened types. The first broken bars observed in both monotonic and cyclic phases of tests are located near one of four corners, and the crack lines then develop to the centre of the sheets. No bar is locally buckled in monotonic tests. In almost cyclic tests, the maximum shear forces have been attained on the cycle on which first broken bar has been observed. The maximum shear forces of small EMP specimens in monotonic tests are dependent on the voids of the sheets. With nearly the same voids, ultimate shear forces of flattened type specimens are much greater than those of normal types. Nevertheless, it is observed that maximum displacements of flattened types are much less than those of normal types and the ductility of normal types are much greater than that of flattened types.

7 CALIBRATIONS OF THE MODELS ON TESTS

As observed from the tests, all EMP loaded in shear behave in a very ductile and stable way. Their behaviour is similar to that of steel plate shear wall (SPSW) used in US, Canada and Japan to seismically upgrade structures. Therefore it is possible to envisage the use of EMP to retrofit or upgrade structures for seismic actions. The test results provide useful information, but are not enough to represent the behaviour of all other types of EMP. To apply EMP to existing RC-MFR, it is necessary to develop a simplified model for EMP loaded in shear. FINELG code, a full nonlinear code developed at University of Liege, is used to model EMP. Each bar of a rhomb shape stitch is modelled as a 3D beam with warping at the middle of the beam being taken into account. As clearly seen from the tests, there are only global buckling of EMP and no buckling of an individual bar, so in the model buckling of each bar is neglected. Material properties of EMP are exploited from tensile tests of bars. Figure 13 and 14 present the behaviour of EMP in the tests and numerical simulations. It can be seen that results from numerical simulations and tests fit well together.

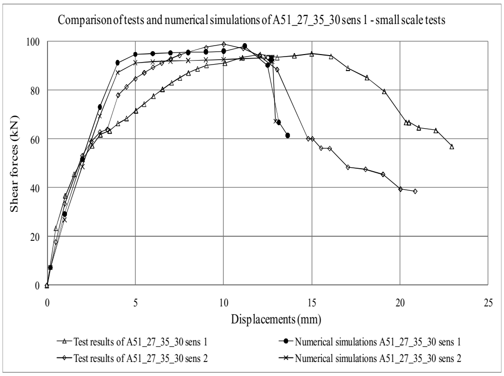

Figure 13 – Comparison of behaviour between tests and numerical simulations in monotonic loading

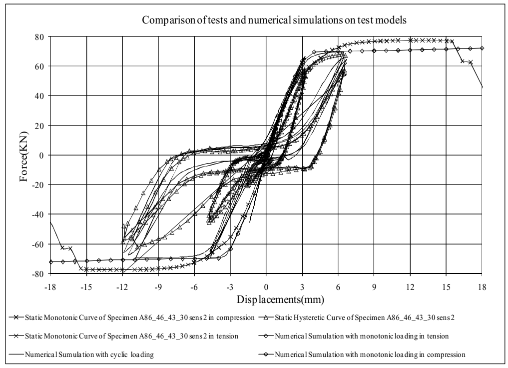

Figure 14 – Comparison of behaviour between tests and numerical simulations in cyclic loading

8 PERSPECTIVES

The next steps of the research on expanded metal material are:

- To improve the analytical model representing Expanded Metal Panel behaviour.
- To make numerical simulations of EMP of all dimensions under cyclic loading and seismic excitations with representation of the hysteretic behaviour of expanded metal sheets.
- To model RC-MRF with and without EMP.

ACKNOWLEDGEMENTS

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