Annexe 6

Etude expérimentale de la résistance de panneaux de metal déployé soumis à des solicitations cycliques de cisaillement.

Experimental Study of the Resistance of Expanded Metal Panels Submitted to Cyclic Shear Tests

Abstract

With the aims at characterizing the mechanical properties of expanded metal (MD) material and expanded metal shear panels (EMSP) under seismic excitations, the research on Expanded Metal material is underway at University of Liege. Many tensile tests are first performed to characterize the mechanical behaviour of MD material. Tests of EMSP in small scale, subjected to shear loading, are then performed to determine the effectiveness of each product of MD. Finally, tests of EMSP under shear loading in large scale are carried out to propose the hysteretic behaviour of EMSP.

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I.1 Introduction

I.1.1 Statement of problem

Expanded metal or Métal Déployé (MD) is not a new construction product, however, there is a very few studies on its mechanical characteristics because it is seldom used in structural applications. The complete products from MD, as introduced in chapter 3, are rectangular expanded metal sheets (EMS) with the approximate dimensions about ±2500mmx±1250mm. Each EMS includes a lot of constant cross section bars forming many rhomb-shape stitches on the sheet. A rhomb-shape stitch of an EMS is constituted by four bars which are almost exactly the same in geometric dimensions. In order to obtain a larger panel there need to combine several original sheets by using welded connections or other types, etc.

Initialising the idea to apply MD material on structural fields, some research on MD has been carrying out. One of its expected structural applications is to use MD to retrofit and upgrade existing reinforced concrete frames, which are subjected to seismic excitations. Physically, an earthquake is a result of a sudden move between main tectonic plates, covering the surface of the globe. The seismic actions, caused by an earthquake and applied to a structure, is a ground movement with horizontal and vertical components ([4] PLUMIER, 1/2008). In general cases, the vertical component is about a half or even less of the horizontal component. Because of less effect than horizontal component, when designing a structure taken into account the effects of an earthquake, the vertical component is usually neglected, and the horizontal component is likely to be the mainly specific feature. There are several procedures to represent the seismic actions such as map-based procedures and site-specific procedures. Map-based procedures use maps of PGA to define seismic input at different hazard levels and under different site conditions ([5] - M.Fardis, E.Carvalho, A.Elnashai, E.Faccioli, P.Pinto and A.Plumier). With the aids of maps of PGA, the earthquake ground motion at a given site is usually characterized by the response spectrum or accelerograms (artificial or recorded accelerograms). The simplest way to apply the earthquake loads on the structures by using response spectrum is that seismic actions will be replaced by equivalent lateral forces or shear forces. Equivalent shear forces are dependent on the structure's properties (stiffness, mass, periods…) and on spectral acceleration ordinates that correspond to both PGA at a given site in and the structures' periods.

It is expected that with the presence of MD on reinforced concrete moment resisting frames (RC-MRF), MD will act as additional elements to resist shear forces generated from earthquakes. In practice, ordinary spans and height of a RC-MRF are about from 2mx3m to 8mx5m. Apparently, it is necessary to combine some EMS to obtain a bigger expanded metal panel to fit the real dimensions of RC-MRF. This new panel, which is a combination of some original expanded metal sheets, is called as an expanded metal shear panel (EMSP).

Up to present, the concept of using EMSP as the lateral resisting elements of bracing frames has not been introduced. There is even no publication of mechanical properties of EMSP. Keeping in mind of determining the behaviour of EMSP under shear loading, experimental study is first used to characterize the properties of EMSP.

To experimentally study the overall behaviour of EMSP, which is formed by a combination of some EMS constituted by a lot of rhomb-shape stitches, mechanical properties of bars forming a rhomb-shape stitch are first determined by tensile tests. After that, tests of EMSP in small scale, with the dimensions less than 1000mm, are performed in monotonic and cyclic shear loading. Tests of EMSP in large scale, which is greater than original dimensions of one sheet, are then studied to determine the monotonic and hysteretic behaviour of EMSP loaded in shear.

To design and perform the tests of EMSP in small and large scales, it is easier if one can find existing materials that their roles in the structures are similar to that of EMSP. Because the role of EMSP in the frames is to resist lateral loads, so the behaviour of EMSP might be similar to that of steel plate shear walls (SPSW).

The concept of using SPSW as main component against earthquakes has been gaining acceptance around the World. A lot of research on SPSW has been carrying out in United States (mainly at University of Beckerly - California), in Japan and in Canada (University of Alberta). Many high-rise structures in several countries have been built using SPSW. According to the development of SPSW in theory and practice, in 1960s, designers, mainly in Japan, had extensively employed longitudinal and transverse stiffeners of various cross-section shapes on both sides of SPSW to prevent from globally buckling. This allows that the yield stress limit of the web material would be reached prior to any lateral buckling of the plates [13]. The favored approach of American designers consisted of fewer or no stiffeners. However, a thicker plate was required with the aim to prevent the buckling of the web. Generally, at this stage, all designer tried to exploit the pre-buckling shear resistance of SPSW, and of course, post-buckling resistance of SPSW was always ignored. Up to 1961, Basler, K. [14] introduced that a thin web can have considerable post-buckling strength. The post-buckling strength depends on the development of a tension field action, which was first initiated by Wagner [15]. In 1980s and 1990s, some studies on post-buckling behaviour of SPSW have been performing at University of Alberta – Canada [8], [9],[13], at University of Beckerly [7], [10]. A simplified procedure was also proposed for design of SPSW. There are some essential conclusions summarized as follows:

- The contribution of strength of un-stiffened SPSW before global buckling can completely neglected.
- Post-buckling strength of un-stiffened SPSW is controlled by the development of tension field action.
- Pinching effect is one of the most important factors of hysteretic behaviour of SPSW.
- With the presence of stiffeners, shear resistance of SPSW can be considerably increased.

Based on the results of studies on the behaviour of SPSW, the experiments on EMSP will be designed. The dimensions and types of MD are chosen so that the tests are economic and able to cover overall behaviour of all existing expanded metal material.

I.1.2 <u>Objectives of the experimental study</u>

The main aim of studying expanded metal shear panels is to apply this type of material on real structures, particularly on the reinforced concrete structures, which are subjected to lateral forces like wind and earthquakes. It will be seen later, the expanded metal material will play a role to increase the stiffness and the strength of the structures and to absorb the energy generated by earthquakes in term of plastic behaviour by establishing tension diagonal fields, and EMSP possesses many necessarily characteristic properties which are basically beneficial for resisting seismically induced loads. Keeping in mind primary objective of using EMSP, experimental program is designed to study the behaviour of EMSP when subjected to extreme cyclic loading, such as would be expected in a severe earthquake.

In short, the objectives of this experimental investigation are:

1. To determine the mechanical characteristics of MD material.
2. To find the effective types of MD material for structural applications.
3. To observe the performance of the EMSP monotonically subjected to the shear loading.
4. To establish the hysteretic model for EMSP.
5. To recommend additional areas of interest for future investigations

I.2 Design of experiments

I.2.1 Introduction

The experimental investigation is performed in three stages: (1) tests to determine mechanical properties of MD material; (2) test in small scale specimens and (3) tests in large scale specimens. Aiming at assessing the global hysteretic behaviour of EMSP under shear loading, there is some considerations when designing the tests:

- An EMSP is a complete panel made from a lot of constant section bars which are successively connected. Apparently, the overall mechanical properties of an EMSP will depend on the properties of the individual bar. Mechanical properties of bars, including elastic modulus, yield stress, ultimate stress, yield strain and ultimate strain, will be characterized by performing tensile tests.

- There are several types of expanded metal products which are normal and flattened types. Amongst all product of MD, which one can be effective to retrofit and upgrade reinforced concrete moment resisting frames (RC-MRF)? In order to select suitable types of EMSP, the tests in small scale specimens will assess the behaviour and effectiveness of each type of EMSP subjected to shear. The testing specimens will be chosen so that they will reasonably present for all products of MD. Besides, the testing frame has to be designed effectively for many small dimensions of EMS. Moreover, the connection between the specimens and testing frame will be considered to choose the connection type for tests in large scale. As far as known that the dimensions of a complete MD sheet are of ±1250mmx±2500mm, for simplifying the test in small scale, the dimensions of testing frame will be less than the dimensions of a MD sheet.

- As having known that when subjected to shear forces, EMSP, like steel plate shear walls, will develop a tension band. This tension band is formed after the EMSP is out of plane unstable. This out of plane instability is unavoidable because of very small dimension in thickness of the sheets. The behaviour of the sheets in shear after buckling can be called as post-buckled behaviour. As we will see in the tests, the tension band developments will control the behaviour of the expanded metal sheets.

- Because one of primary aims is to determine the ultimate shear resistance of EMSP, apparently, all components of the tests must be designed in accordance with this ultimate resistance. It is clear that all mechanical and geometrical properties of all elements of the experiments will be controlled by capacity design.

- To focus on correctly assessing the only behaviour of the EMSP, the test will be designed so that shear loads from the machine will entirely transmit to the EMSP.

- After finishing the tests in small scale, types of MD will be decided for tests in large scale. In addition, the effectiveness of type of connection will also be assessed with the aims to determine the type of connection between testing frame and specimens in large scale tests.

- For all tests in small and large scales, ultimate shear resistances and maximum displacements of EMSP are the essential criteria for designing the testing frames and choosing the actuators and measurement devices.

- Knowing that final objectives of the experimental studies are to characterize the hysteric behaviour of EMSP loaded in shear, in both stages (2) and (3), tests will be performed in two phases accordingly to ECCS 1996 [12]: monotonic phase and cyclic phase.

Accounting for all considerations, all the components of the tests will be designed. Figure -1 and Figure-2 show the overviews of tests in small and large scales.

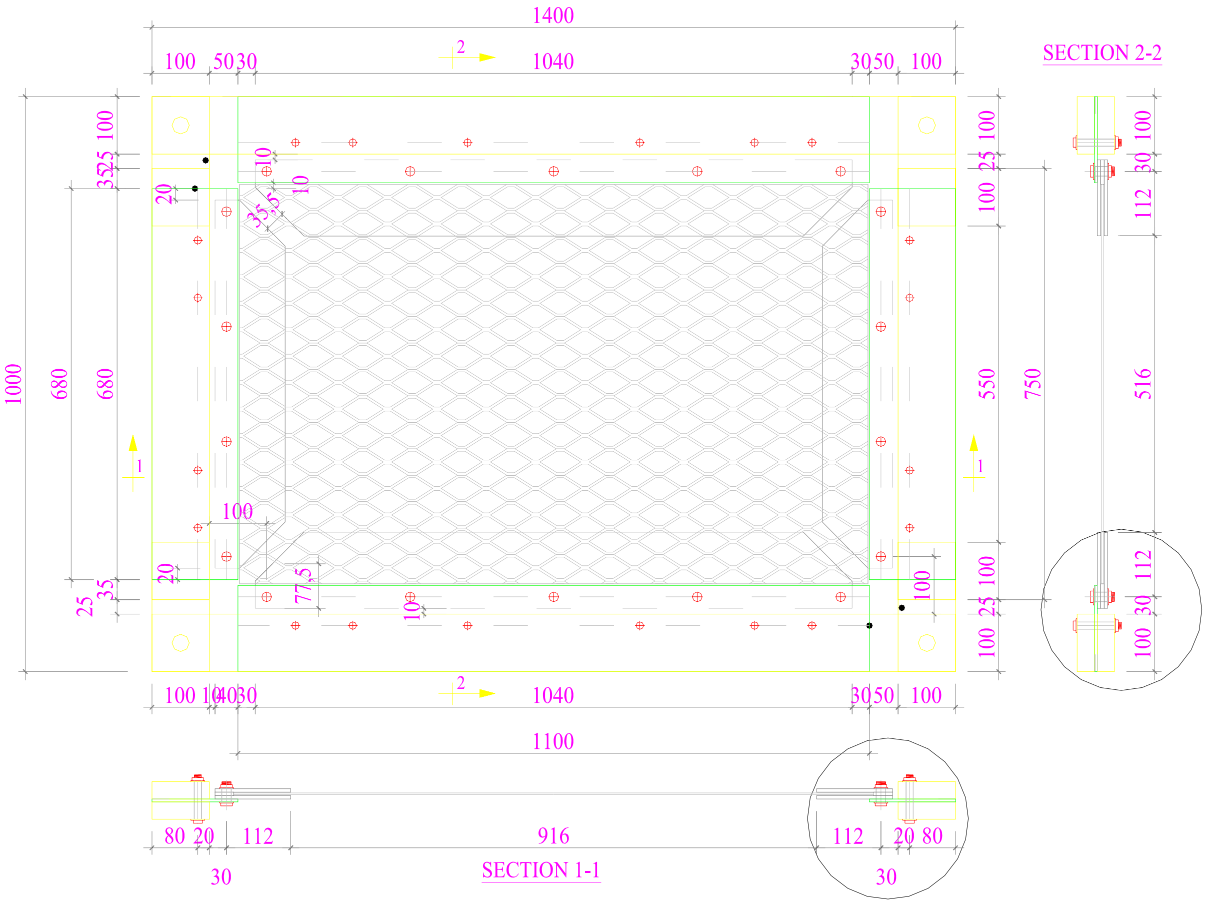


Figure -1 – Overview of all components of tests in small scale

It can be seen from two figures that in both experiments, there are three main components, which are EMSP, testing frame and testing devices including actuators and measurements. EMSP is connected to testing frames by using gussets called 'intermediate plates', which will be connected with EMSP by welded or glue-epoxy connections and with testing frames by bolt connections.

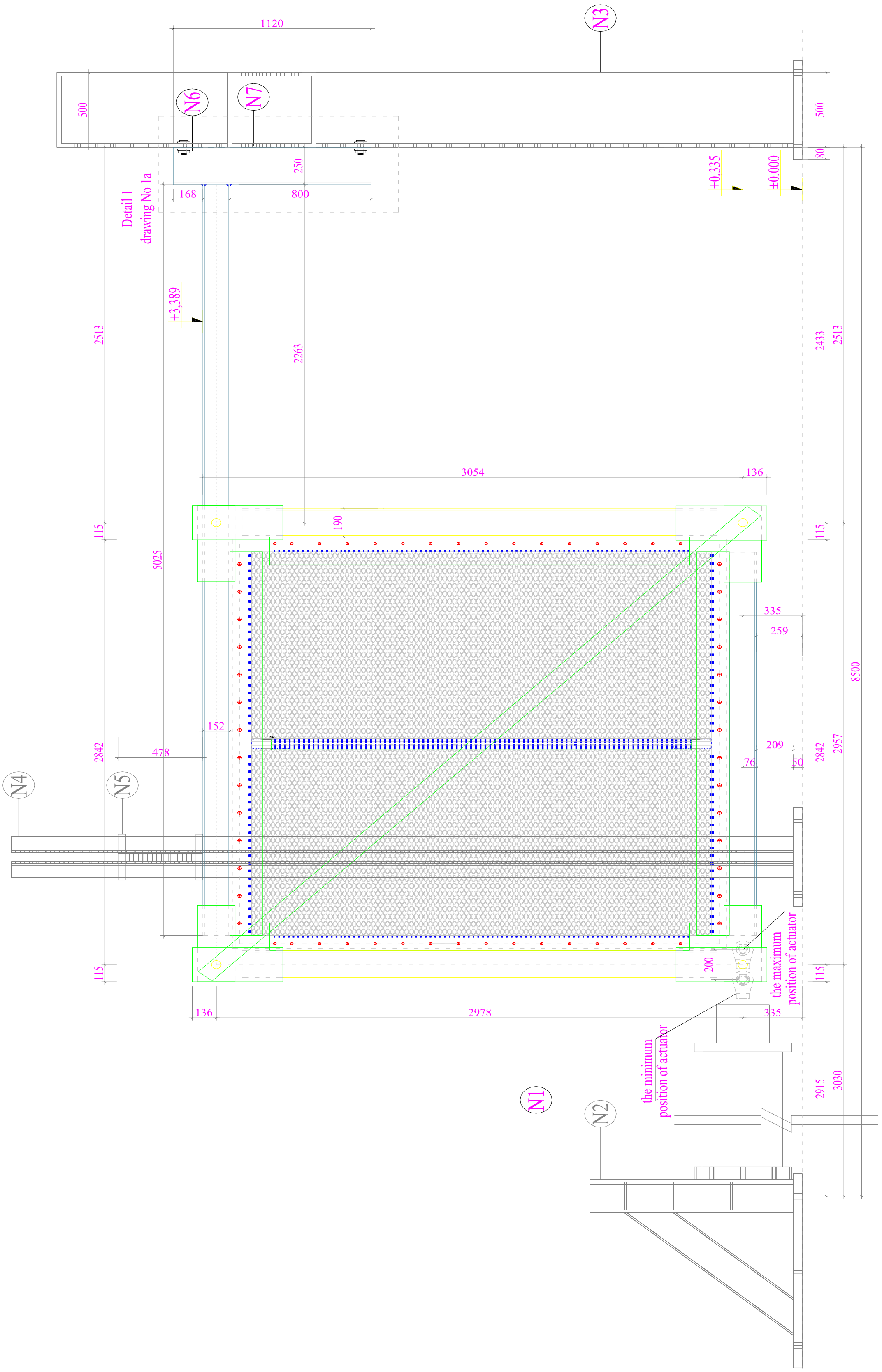


Figure-2 – Overview of all components of tests in large scale

I.2.2 Specimens

As introduced in chapter 3, the differences of MD products can be catalogued by the types of MD, which are normal or flattened, and the dimensions of each rhomb-shape stitch are used to distinguish the MD products in each type. The dimensions of a rhomb-shape stitch include LD, CD, A and B, which are used to name for the MD products as LD_CD_A_B for the normal type and ALD_CD_A_B for the flattened type.

Specimens, which are chosen for the experiments, should include both normal and flattened types. Moreover, in order to compare the behaviour between EMS, all specimens are intended choosing so that the thicknesses of the bars in all EMS are the same. The MD of flattened type is A51_27_35_30 and A86_46_43_30. The other MD of normal type is 51_23_32_30 and 86_40_32_30.

I.2.2.1 Specimens for tensile tests

To do the tests in tension of MD, 3 MD rods of each specimen with the length of about 500mm are removed from MD sheets. Figure-3 shows the specimen prepared for the tensile test. With four kinds of MD products, there are 12 specimens prepared for the tests in tension.

Figure-3 - Specimen for tensile tests

I.2.2.2 Specimens for shear tests in small scale

It is well-known that there are two types of MD products. In each type, there are a lot of different kinds which can be distinguished by the differences in dimensions of rhomb-shape stitches. Choosing the criterion, which can be used to clarify testing specimens, is not an easy task. There is some considerations, which has to be taken into account when clarifying testing specimens.

- Firstly, types of testing specimens should have the characteristics which are easily used to distinguish between testing specimens.
- Secondly, the testing specimens should be easily clarified not only in this small scale tests but also in large scale tests.

Thirdly, keeping in mind that the final objectives of this study are to use EMSP to retrofit reinforced concrete existing frames subjected to seismic actions, choosing the suitable types of MD material and studying the types of the connections between EMSP and existing components of the retrofitted frames … are also important. Primarily focusing on the pure shear behaviour of the sheets, the connections must be ensured that there will be no failure on that during the tests. It is clear that the connection material should have enough strength, stiffness to resist the ultimate responses generating from the small EMSP. Two types of connection material are chosen for testing specimens: weld and glue-epoxy materials. Figure -4 and Figure-5 show the overviews of two types of connection.

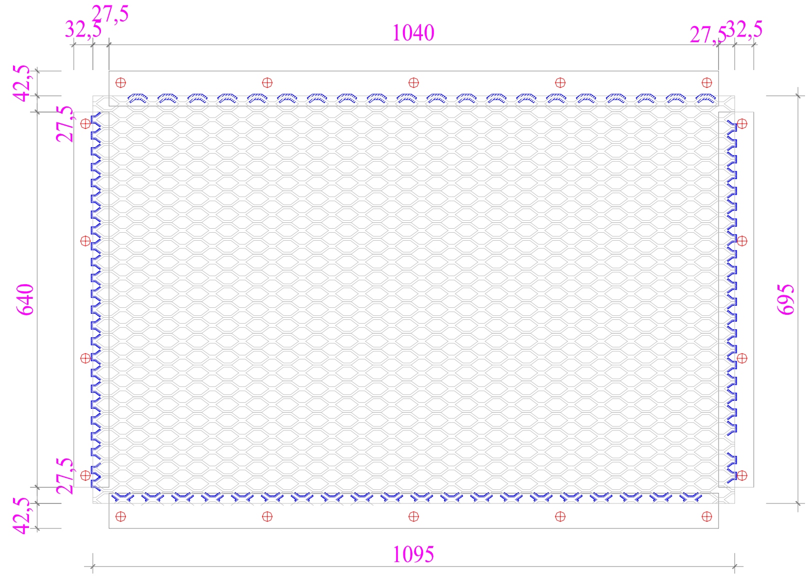


Figure -4 – Welded connections

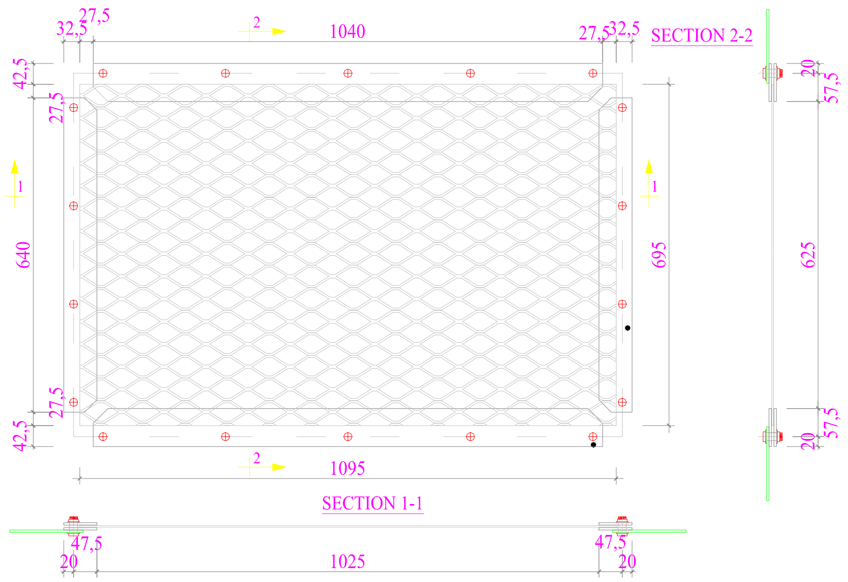


Figure -5 – Glue-epoxy connection

- Fourthly, there are 4 different kinds of MD products in these small scale tests. For each kind, there are two directions which can be possible to erect the EMSP onto the testing frame. Particularly, the differences of two directions are the two ways to fabricate the specimens to the testing frame: (1) dimension LD of rhomb shape stitch is parallel to the longer dimensions of the frame, and (2) on the contrast, dimension LD is parallel to the shorter dimensions of the frame. Figure -6 presents two possible directions forming a complete testing specimen.

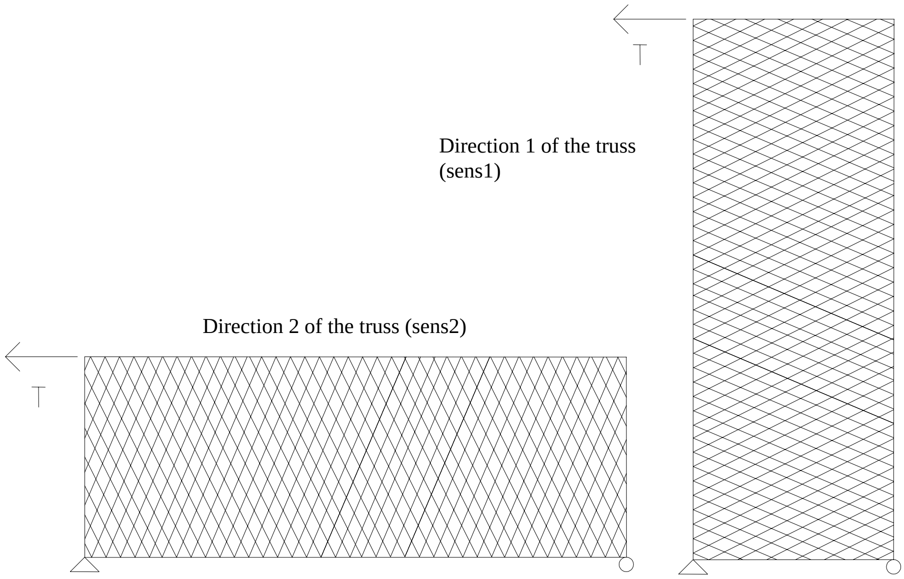


Figure -6 – Notions of sheet directions

Taking into account for all considerations, the criteria used to clarify testing specimens are decided to be the combination of connection types, directions of erecting EMSP on testing frame and particular name of EMSP types. All specimens are summarised hereafter in Table 3.1.

Figure -7 presents an overview of a typical specimen before testing. The small EMSP is connected to four gussets by welding, and by using bolts these gussets will be connected to the testing frame. The gussets have to be designed to be able to resist the maximum shear force which generated on the sheet. Figure -8 shows the small EMSP with welded connections after connecting a MD sheet to four gussets.

Table -1 – Testing specimens in small scale tests

N^0	Specimens	LD (mm)	CD (mm)	A (mm)	B (mm)	Type of MD	Type of tests	Direction of erection
1	A51_27_35_30 sens1 – welded connections	51	27	3,5	3,0	Flatten	Monotonic	LD // to shorter side of the frame
2	A51_27_35_30 sens2 – welded connections	51	27	35	30	Flatten	Monotonic	CD // to the shorter side of the frame
3	A86_46_43_30 sens1 – welded connections	86	46	43	30	Flatten	Monotonic	LD // to the shorter side of the frame
4	A86_46_43_30 sens2 – welded connections	86	46	43	30	Flatten	Monotonic	CD // to the shorter side of the frame
5	51_23_32_30 sens1 – welded connections	51	23	32	30	Normal	Monotonic	LD // to the shorter side of the frame
6	51_23_32_30 sens2 – welded connections	51	23	32	30	Normal	Monotonic	CD // to the shorter side of the frame
7	86_40_32_30 sens1 – welded connections	86	40	32	30	Normal	Monotonic	LD // to the shorter side of the frame

8	86_40_32_30 sens2 – welded connections	86	40	32	30	Normal	Monotonic	CD // to the shorter side of the frame
9	A51_27_35_30 sens1 – welded connections	51	27	3,5	3,0	Flatten	Cyclic	LD // to the shorter side of the frame
10	A51_27_35_30 sens2 – welded connections	51	27	35	30	Flatten	Cyclic	CD // to the shorter side of the frame
11	A86_46_43_30 sens1 – welded connections	86	46	43	30	Flatten	Cyclic	LD // to the shorter side of the frame
12	A86_46_43_30 sens2 – welded connections	86	46	43	30	Flatten	Cyclic	CD // to the shorter side of the frame
13	51_23_32_30 sens1 – welded connections	51	23	32	30	Normal	Cyclic	LD // to the shorter side of the frame
14	51_23_32_30 sens2 – welded connections	51	23	32	30	Normal	Cyclic	CD // to the shorter side of the frame
15	86_40_32_30 sens1 – welded connections	86	40	32	30	Normal	Cyclic	LD // to the shorter side of the frame
16	86_40_32_30 sens2 – welded connections	86	40	32	30	Normal	Cyclic	CD // to the shorter side of the frame
17	A51_27_35_30 sens1 – glue epoxy connection	51	27	3,5	3,0	Flatten	Cyclic	LD // to shorter side of the frame
18	A51_27_35_30 sens2 – glue epoxy connection	51	27	35	30	Flatten	Cyclic	CD // to the shorter side of the frame
19	A86_46_43_30 sens1 – glue epoxy connection	86	46	43	30	Flatten	Cyclic	LD // to the shorter side of the frame
20	A86_46_43_30 sens2 – glue epoxy connection	86	46	43	30	Flatten	Cyclic	CD // to the shorter side of the frame
21	51_23_32_30 sens1 – glue epoxy connection	51	23	32	30	Normal	Cyclic	LD // to the shorter side of the frame
22	86_40_32_30 sens1 – glue epoxy connection	86	40	32	30	Normal	Cyclic	LD // to the shorter side of the frame
23	86_40_32_30 sens2 – glue epoxy connection	86	40	32	30	Normal	Cyclic	CD // to the shorter side of the frame

Figure -7 – Overview of specimen A_86_46_43_30 sens 1 – welded connections before testing

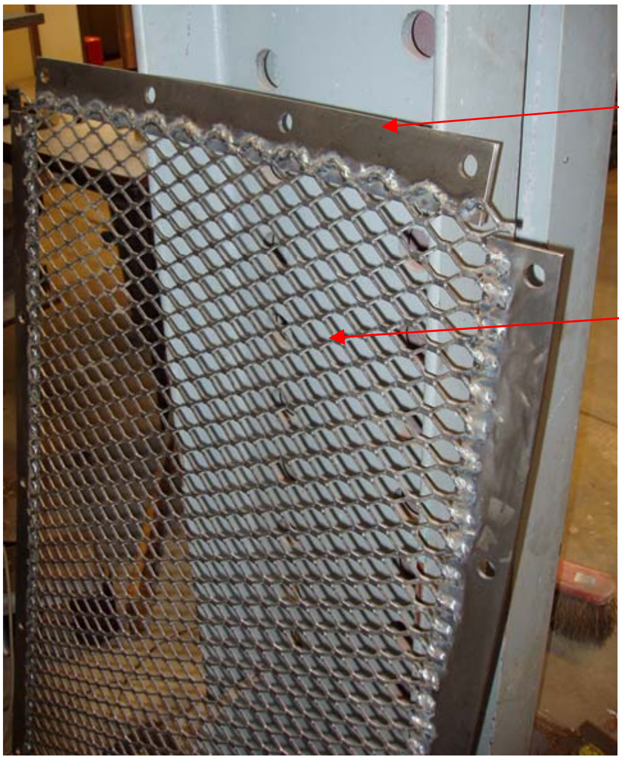


Figure -8 – Small EMSP specimens – with welded connections

It is worth noting that there is only one testing frame used for all specimens of both welded and glue-epoxy connections. The overall dimensions of this frame are constantly kept for all tests. However, because of the differences in the connection materials, the dimensions of EMSP specimens of both types are considerable different. This is obvious because the strengths of connection materials are quite different, and it results in a different length of anchorage between EMSP and four gussets to be sure that there is no failure in the connection during the tests. Figure -9 shows the overview of a glue-connection specimen before testing.

Figure -9 – Glue-connection specimens before testing

I.2.2.3 Specimens for shear tests in large scale

The experiments in large scale will be carried out after gathering and analysing the data obtained from the results of tests in small scale. Similarly to the tests in small scale, some considerations must be constantly kept in mind when clarifying and selecting the specimens used in large scale tests:

- The effective type of MD products to retrofit RC-MRF: It will be seen later, in section I.4, in both normal and flattened types of MD products, the flattened type seems to be more suitable for RC-MRF in terms of strength, stiffness and especially of connections with RC-MRF than the normal type.

- Overall dimensions of the specimens: It should be noted that the dimensions of an MD sheet are about ±1250mmx±2500mm, and the popular dimensions of beam spans and story's heights of RC-MRF are about from ±2000mmx3000mm to ±8000mmx5500mm. Apparently, it is necessary to combine some MD sheets to form a complete EMSP for applying it in real RC-MRF. In accordance with tests in small scale, welded and epoxy-glue connections can effectively be used for connecting MD sheets together and connecting EMSP with testing frame. However, considering the economical aspects and making it easy to fabricate, welded connections are selected to combine MD sheets together and to connect EMSP to the testing frame.

- Capacity of testing machine and economical consideration: Ultimate shear resistances and ultimate displacements of EMSP generating during the tests are the most important factors, which mainly influence not only on the dimensions and mechanical properties of testing components but also on the choice of testing machine. The scale, simplicity, cost of experimental program dictate that six specimens can be tested.

- Connections between specimens and testing frame: A very crucial consideration is the connection between EMSP and testing frame. Thanks to the tests in small scale, it can be concluded that welded connections have many advantages than epoxy-glue connections.

- Fabrication procedures: To setup the tests in large scale, all components such as specimens, testing frame, testing machine and transducers will be considered in term of fabricating process.

Taking into account for all considerations, a combination of two MD sheets is selected as the testing specimen. Two MD sheets are connected together and to testing frame by using T-shape steel plates as shown in Figure -10 to form a complete EMSP. These T-shape steel plates are welded to EMSP and bolted to testing frame.
It is worth noting that before erecting the EMSP to testing frame in lab, EMSP is made to be very stiff by using many additional fish plates. These fish plates are welded to all T-shape steel plates to be sure that there is no initial deformation occurring in EMSP because of fabrication or transportation.
Six test specimens are listed in Table -2.

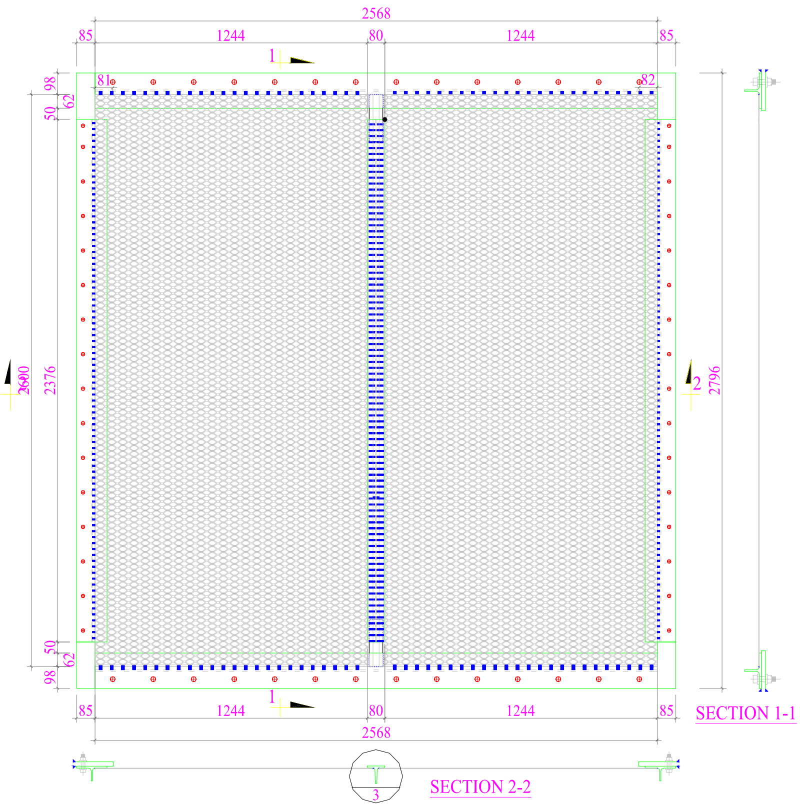


Figure -10 – EMSP Specimen in large scale tests

Table -2 – Summary of all specimens in large scale tests

N^0	Specimens	LD (mm)	CD (mm)	A (mm)	B (mm)	Type of MD	Type of tests	Dimensions of EMSP (mm) (widthxheight)
1	A51_27_35_30 – welded connections	51	27	3,5	3,0	Flatten	Monotonic	2580x2630
2	A86_46_43_30 – welded connections	86	46	43	30	Flatten	Monotonic	2580x2630
3	A51_27_35_30 – welded connections	51	27	35	30	Flatten	Cyclic	2568x2600
4	A86_46_43_30 – welded connections	86	46	43	30	Flatten	Cyclic	2580x2630
5	A51_27_35_30 – welded connections	51	27	35	30	Flatten	Dynamic	2580x2630
6	A86_46_43_30 – welded connections	86	46	43	30	Flatten	Dynamic	2580x2630

I.2.3 <u>Testing frame</u>

I.2.3.1 Testing frame in small scale tests

The testing frame is to be thoroughly considered in many aspects: stiffness, strength, dimensions, flexibility, suitability for monotonic and cyclic tests, connection between the testing frame and EMSP.

Firstly, the testing frame should possess adequate stiffness to resist shear force which can be up to the ultimate load of the biggest commercial EMSP without considerable deformations. All the components of the testing frame should not be deformed during all monotonic and cyclic tests. This ensures that the results from tests will be the behaviour of EMSP only.

Secondly, another consideration was the dimensions of the sheared sheets which would influence on the dimensions of the testing frame. It is very good if it is possible to test many various dimensions with different types of small EMSP. However, depending on the real largest dimension of EMSP which is about ±1.25m in width and on the costs of experiments, there were some limitations for choosing sheet dimensions. Additionally, in these testing phases, the pure shear behaviour of only the MD sheets, not accounting for either their behaviour in real structures or the interaction between sheets and frame elements (beams or columns), is mainly interested.

Thirdly, the testing frame should be suitable for different types of MD sheets and be convenient for cyclic and monotonic tests. As mentioned above, at this stage, it is not necessary to reproduce true scale tests of building frame, but it is necessary to get enough stitches of the EMSP to obtain the global behaviour of the MD sheets, including as well resistance as stability phenomena. Because of that, the testing frame must be suitable not only for small rhomb shape stitches but also for the biggest ones. In addition, it is also essential to do tests on squared but also on rectangular sheets with different aspect ratios of EMSP.

After assessing many considerations, it has been decided to build a frame with variable dimensions from 400mmx800mm to 1000mmx1400mm. Because of construction considerations, dimensions were variable with a step of 100mm. Figure -11 gives a global view of the frame for shear tests in the configuration of the biggest dimensions.

Figure -11 - Global view of the frame for shear tests

In the testing frame, there are four sides hinged at the corners, and they are connected together by four steel cylindrical axes having a diameter of 30mm and by two pieces of the fork at each corner. To make sure that all hinges are rotated freely, four composite rings are added within four axes.

Each side of the frame, which consists of two 30x100mm rectangular section bars, is used to stably keep a stretched plate by means of bolts having a diameter of 20mm and the distance of 100mm. These stretched plates, which have been designed to connect the frame to EMS specimens by bolts having a diameter of 20mm and distances of 250 and 300mm, must be able to resist the same ultimate shear force like the gussets in small EMSP specimens. They have sections of 50x60mm. With these stretched plates, bolts were used to fix the EMSP to the frame without disassembling the whole frame after each test. The diameter and the step of bolts are deliberately determined so that they are stiff enough to sustain the largest shear stresses generated from the sheets. Figure -12 presents a view of the section of the sides at a corner of the frame.

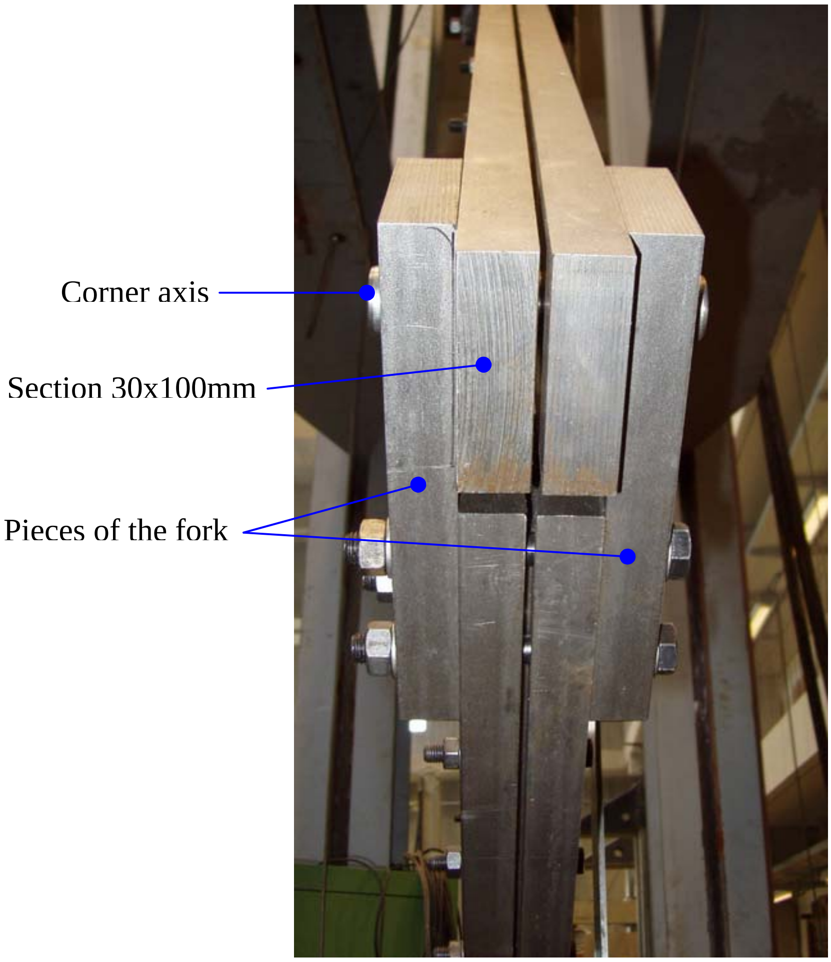


Figure -12 – Section of the testing frame and joint between two sides of the frame

It is easy to observe the extremities of the corner axis and the forks that allow superimposing the extremities of two sides to connect them together. The forks also allow changing the frame dimensions flexibly. Additionally, at two of the four corners, which were used to apply the pulling or pushing forces by a jack, additional biggest forks were added around the first forks. They can be observed in 0. These additional folks play a very important role in monotonic and cyclic tests, because they not only are used to apply loads but also can prevent the frame from instability when the frame is in compression.
In order to simplify experiments, the shear forces are applied by a hydraulic jack along just only one diagonal of the frame in both tension and compression directions. In fact, as explained in Figure -14, this axial force acting on the diagonal of the frame is completely equivalent to a direct shear force.

With this simplicity, it is really easy to implement the both monotonic and cyclic experiments with the fixation of only one hinged corner of the frame. The opposite hinged corners will be pulled only to model for monotonic tests and be pulled and pushed to model for cyclic tests.

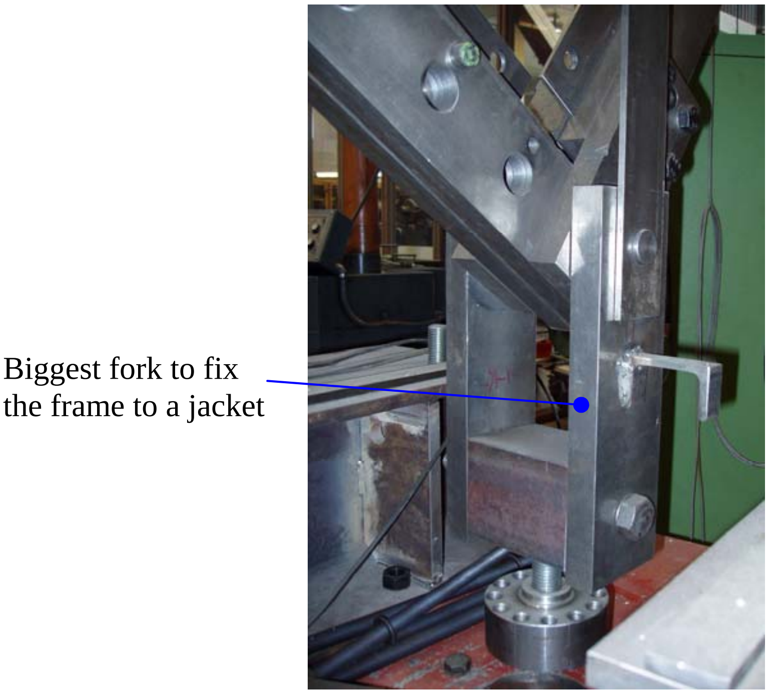


Figure -13 – Additional fork for applying force

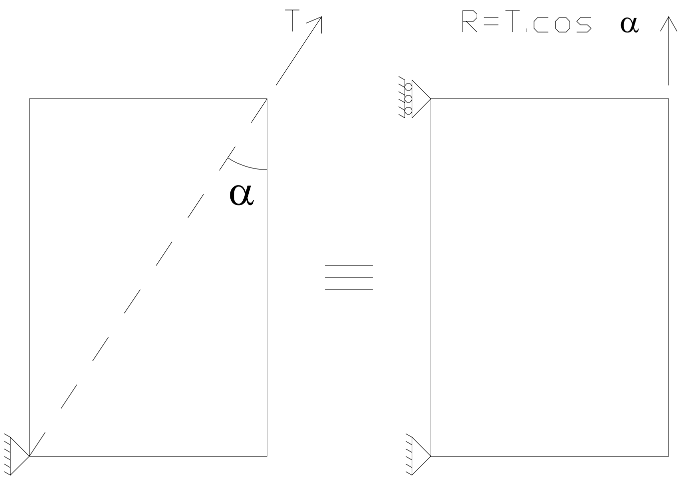


Figure -14 – Notions of shear loads acting on the frame

To measure the displacements of the specimens, as illustrated on Figure -15, the variations of the diagonal length corresponding to each step of increasing force will be measured progressively. The applied forces and the displacements in the direction of the diagonal of the frame are recorded at each step. Furthermore, taking into account differences between the sheets and the hydraulic jack, two series of displacement values corresponding to the displacement of the sheet and the jack are also simultaneously recorded. The displacements, which are perpendicular to the plane of the sheet at the centre of EMSP, will not be concerned because it is not necessary to take into account the out of plane behaviour of the sheets.
The testing machine used in the test is SCHENCK 2500KN. The maximum load is about ±2500KN.

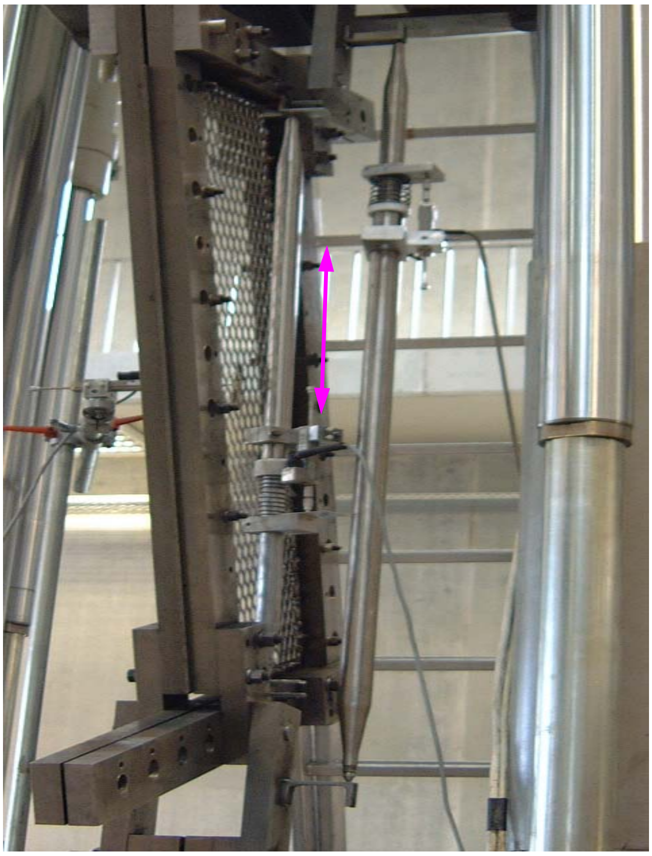


Figure -15 – Displacements measurements on an expanded metal sheer test

I.2.3.2 Testing frame in large scale tests

The full size of the test, as shown in Figure -16, presents a complete figure of EMSP and the testing boundary frame with overall dimensions corresponding to the centre lines of the framing members, that is, a bay width of ±2600mm and story height of ±2580mm. These dimensions are chosen with the purposes that they are approximately close to the real structural dimensions and account for the real dimensions of expanded metal sheet while still satisfying the expenses of testing program and constraints imposed by physical space limitations in the laboratory and the limitations of testing devices.

The testing frame includes two steel columns and two steel beams. The dimensions of columns and beams are taken as HE 200 and HE 160, respectively. They are hinged to each other by using some additional fish plates and four axes having the diameters of 50mm. Similarly to the tests in small scale, only focusing on pure behaviour of EMSP loaded in shear and to be sure that all forces from actuator will be entirely transmitted to EMSP, 8 composite rings are used to connect beams with columns, and 2 composite rings are used to connect actuator with the testing frame, as shown in Figure -18.

In order to link testing specimens and the testing frame, four fish plates, which run along four boundary beams and columns, are designed. These plates are connected with boundary elements by fillet weld. The dimensions of those plates, which are linked with the beams, are about 2568mm x 185mm x 20 mm in length, width and thickness, respectively. The other fish plates, which are connected with column, have the length of 2367mm, width of 185mm and the thickness of 20 mm. Figure -17 show the detail of the connection between testing specimens and a column of the testing frame.

The testing frame is constrained by two fixed frames and a fixed column of the laboratory. As shown in Figure -16, two existing frames are intended to rigidly fix with the testing frame by welding in order that the top beams will not be bent by loads during the tests. The inertial axial forces generated in the columns by vertical components from EMSP will be almost transmitted to two existing frames.

Figure -16 – Global view of tests in large scale

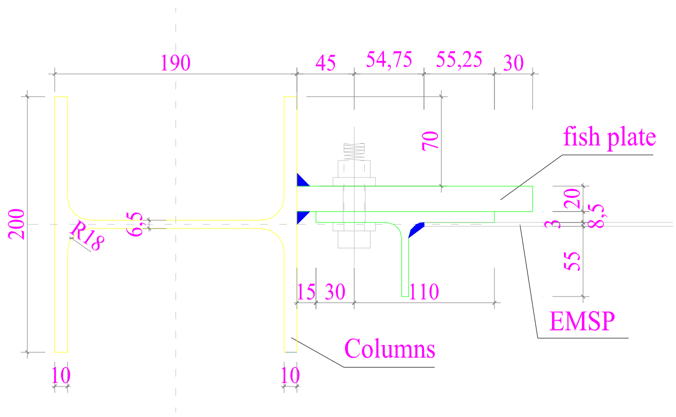


Figure -17 – Detail of connection between testing frame and testing EMSP

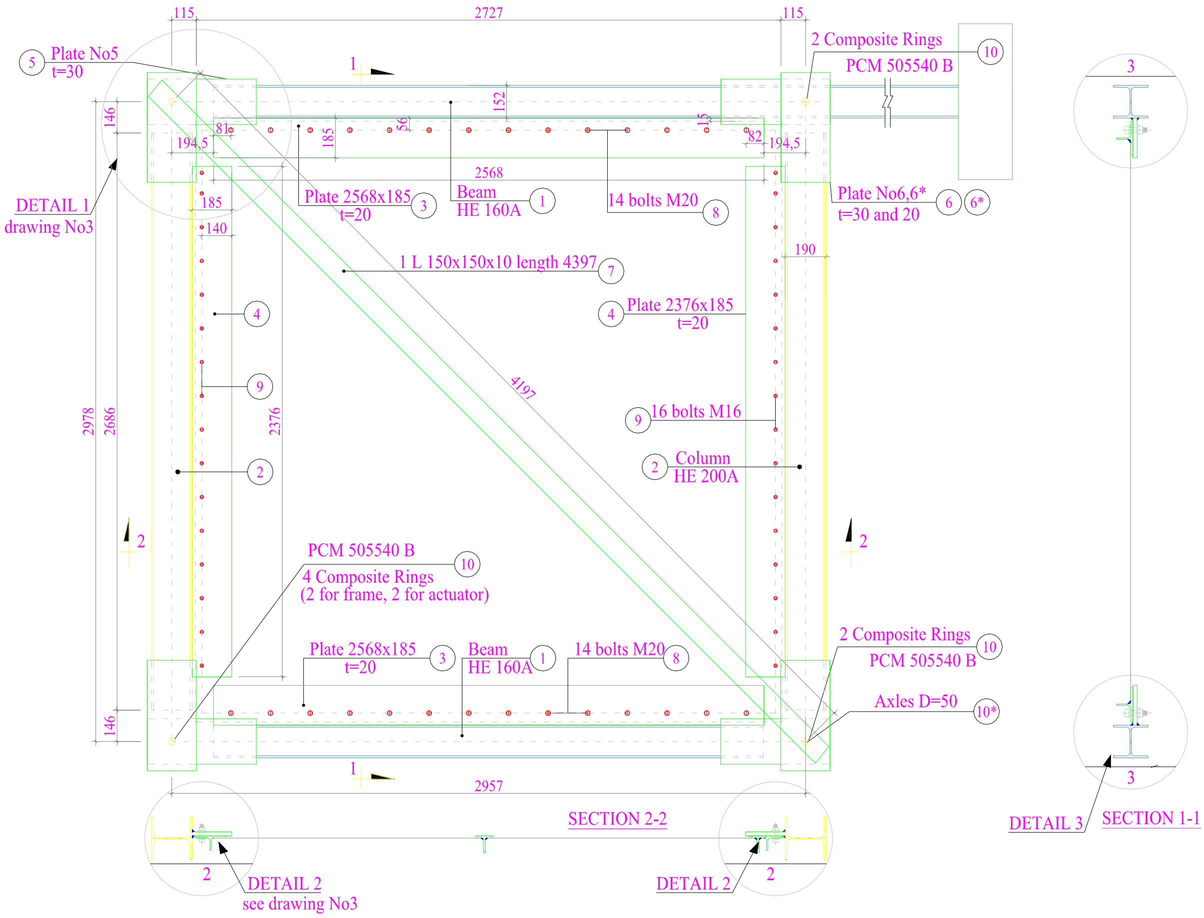


Figure -18 – Testing frame

It is worth noting that all the components of the testing frame are designed in accordance with Eurocode 3 [R4.14 - Eurocode 3-1993: Design of steel structures]. In addition, all mechanical properties and dimensions of them are designed based on capacity design rules relating to ultimate shear resistance and ultimate displacements of the testing EMSP. They are also chosen so that they will only work in elastic ranges during fabricating and testing.

I.3 Testing procedures

I.3.1 Tensile tests

As presented in section I.1.2, tensile tests are to determine mechanical properties of MD product in general. More particularly, initial stiffness, secant stiffness, Young modulus, strain hardening modulus, yield stress, yield strain, ultimate stress, ultimate strain and ductility of the bars in rhomb shape stitches of EMSP are also the primary objectives of tensile tests. All specimens will be pulled until they are completely broken. Force-displacement relationships will be recorded.

I.3.2 Monotonic test phase

Monotonic test mainly aims at determining relationship between shear force and displacement of EMSP. In addition, from the results of monotonic tests, many properties of EMSP specimens will be evaluated to provide data for cyclic test phase such as: monotonic force-displacement curve, conventional limit of elastic range: F_y^+-conventional yielding force and e_y^+-corresponding displacement, and initial stiffness of specimen.

In this phase of experiments, the forces acting on the EMSP specimens are monotonically increased until complete failures of the specimens can be clearly observed. The displacements, which correspond to each step of monotonically increasing forces, will be recorded simultaneously. In fact, the monotonic tests should be implemented in two opposite directions: compression and tension. However, because of the symmetry of the expanded metal sheets, only the tests of one in two directions will be carried out.

I.3.3 Quasi-static cyclic test phase

Cyclic testing procedure is based on the recommendation of ECCS – 1986 [R4.10.]. Cyclic testing phase is divided into two stages. A first stage is a monotonic test used to define the parameters of the cyclic test. A second stage is to test EMSP specimens in cyclic loading. First stage procedures are listed in Table -3.

Table -3 – Calibrating monotonic tests

Step	Descriptions
1	Evaluating the tangent at the origin of the Force-displacement curve; it gives a tangent modulus $E_t^+ = \tan(\alpha_y^+)$
2	Locating the tangent that has a slope of $\frac{E_t^+}{10}$
3	Defining the level of F_y^+ which is the intersection of the two tangents
4	Determining the value of e_y^+ which is the displacement corresponding to that intersection

Second stage could start after having the results from the first stage. In this stage, the EMS specimens will be pulled and pushed successively in many cycles. The tests are run with control displacements. The testing procedure of this stage is presented in Table -4.

Table -4 – Cyclic testing procedures

Steps	Applied displacements in tension	Applied displacements in compression	Number of cycles
1	$e_y^+/4$	$e_y^-/4$	1
2	2* $e_y^+/4$	2* $e_y^-/4$	1
3	3* $e_y^+/4$	3* $e_y^-/4$	1
4	e_y^+	$-e_y^+$	1
5	2* e_y^+	-2* e_y^+	3
>=6	$(2+2n)e_y^+$	$-(2+2n)e_y^+$	3

I.4 Test observations

I.4.1 Tensile tests

Many series of tensile tests are performed to determine mechanical properties of bars of MD products. It is very important to note that the mechanical properties of bars in each type and profile of MD are quite different. In addition, although all tensile specimens are taken from the same profiles of MD but different MD sheets, these properties may also be different. Figure -19 presents the stress-strain relationship of tensile tests and proposals of flattened type.

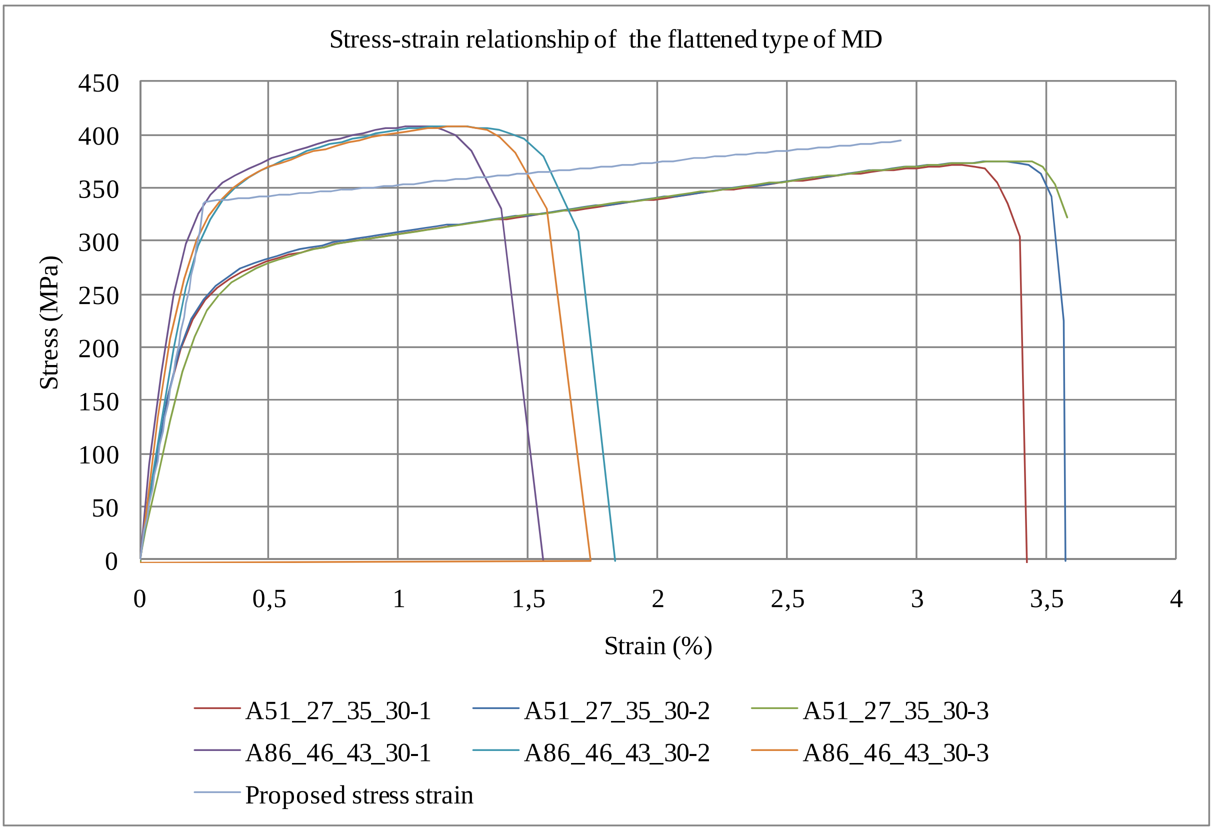


Figure -19 – Tensile test results of flattened type

Mechanical properties and stress-strain relationship of an expanded metal bar are shown in Table -5 and after doing many tests in tension.

Table -5 – Proposed mechanical properties of a MD bar

Initial Stiffness – Modulus E_1(MPa)	Yield Stress (MPa)	Yield Strain (%)	Strain Hardening Modulus (E_t) (MPa)	Ultimate Strain (%)	Ultimate Stress (MPa)
134000	337	0.0025	2139	0.029	393

I.4.2 Small scale tests

I.4.2.1 Monotonic loading test phase

General features:

It should be noted that there is a series of monotonic tests in small scale. Welded connections between the small EMSP specimens and the testing frame are used with the overall dimensions of rectangular EMSP about 660mmx1056mm.

Under monotonic loading, up to the failure it is easy to observe in all tests that the behaviour of all testing specimens can be divided into an elastic stage and a plastic stage. The elastic range starts from the beginning of a test until reaching yield displacement. These yield deformations of all specimens range from 0.85mm (0.12% drift) to 1.17mm (0.18% drift), as shown in Table -6. Beyond the elastic range, all the small EMSP specimens perform plastic deformations until attaining ultimate displacements. During the plastic deformations the section area of bars reduces and the slope of force-displacement curves decreases considerably.

In all tests, there are four couples of two similar tested EMSP in eight testing specimens. In a couple, the expanded metal profile is the same. They are different in the way of setting up to the testing frame as shown in Table -1. Because of this difference, the values of yield displacements, yield force, ultimate displacements and ultimate shear force of each specimen in each couple are slightly different. Figure -22 and Figure -23 show the testing results of welded connection specimens in both flattened and normal types.

In all the specimens, there are some discrete positions which have had visible out-of-plane deformations. These initial buckling deformations are different in each specimen. They become clearer after rather low shear forces are applied. The shapes of buckling waves, as shown in Figure -21, are the same for all testing small EMSP specimens. Although the sheets are prone to global buckling, 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. The section areas of these bars are clearly decreased before being broken. In spite of the fact that some bars are broken, the sheets keep carrying shear forces. It is also observed that after each bar is broken the shear force is suddenly reduced and then increased until the sheets are completely broken. The broken bars first appear at the corners of the testing frame, and then spread gradually to the centre of the sheets. To explain for the reason why broken bars are always first located at the corners of the sheets, it is necessary to determine the relative strains of tensile strips of EMSP. As mentioned, when subjecting to shear loading, two bars of rhomb-shape stitches will work in tension and the others in compression. All bars working in tension will form many tensile strips. After being deformed the relative strains of the tensile strip at the two corners, which are opposite to loading directions, are much greater than middle tensile strips. Figure -20 shows the values of the lengths of some tensile strips before and after testing.

It can be deduced from the Figure -20 that the trains of short tensile strips at left under corner are greater than those of long tensile strips:

$$\frac{144{,}7-131{,}5}{131{,}5}=0{,}1>\frac{459{,}1-426{,}1}{426{,}1}=0{,}7745>\frac{1186{,}1-1107{,}3}{1107{,}3}=0{,}0712\,.$$

All the tests are stopped because small EMSP specimens have been largely deformed. There is no failure either at the weld connections between the expanded metal sheets and the plates or at the bolt connections between sheet-plates and intermediate-plates.

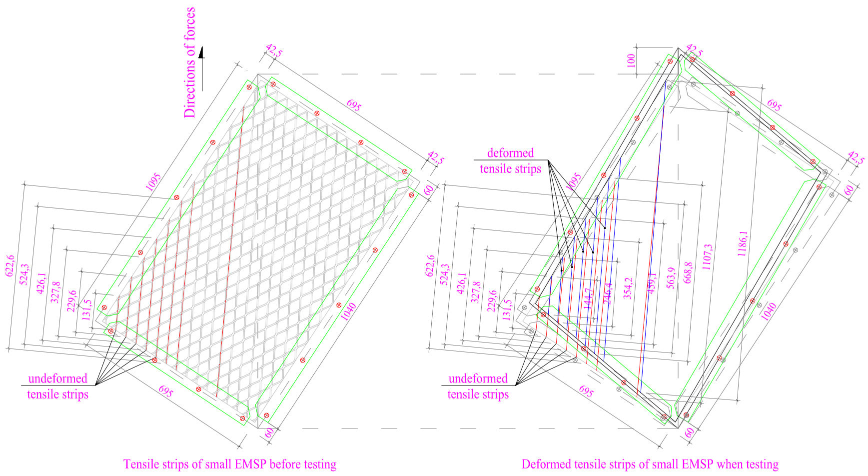
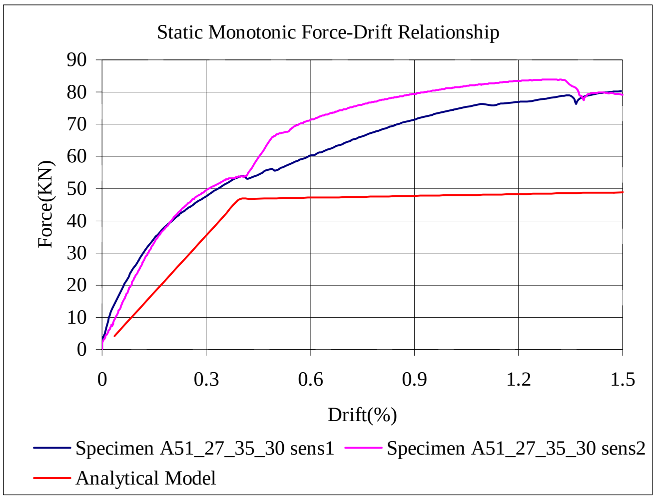


Figure -20 – Positions of tensile strips in tests of small EMSP

Particular features:

Out of the two material types of tested specimens, the normal type buckles more rapidly than the flattened type. The shear forces causing buckling in normal type specimens are lower than in flattened types. In each expanded metal type, the ultimate shear 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 shear 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. Apparently, normal type specimens are more ductile than flattened type specimens. Ductility factors of normal types are twice greater than those of flattened types.

Figure -21 – Buckling shape after testing of specimens – welded connections



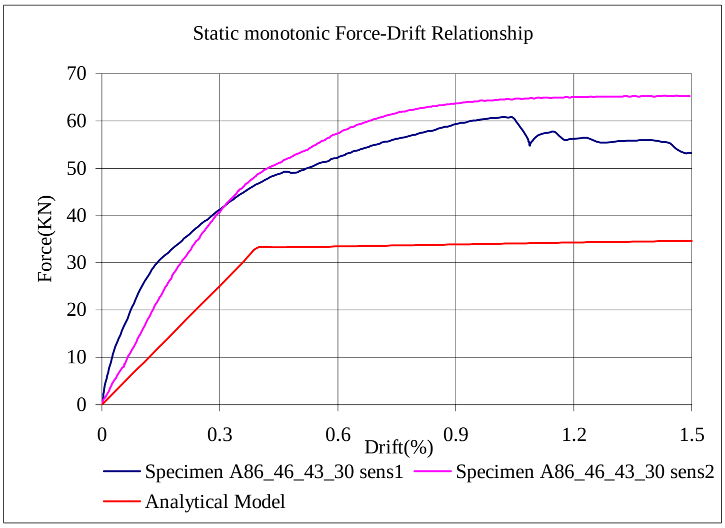
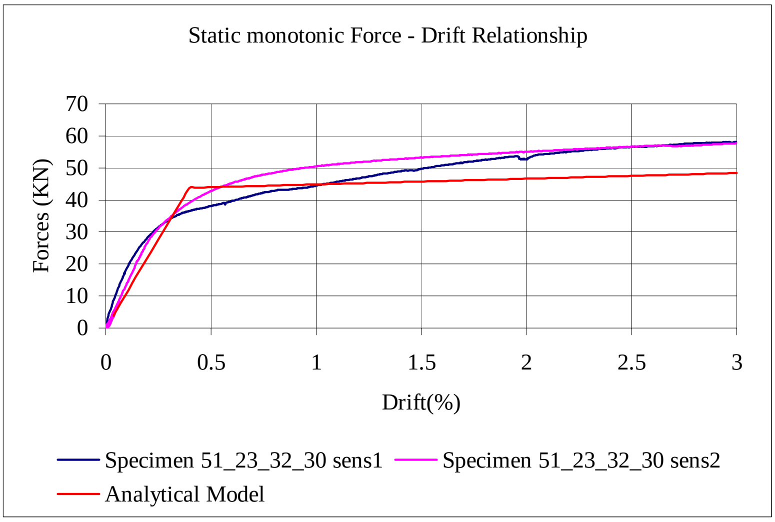


Figure -22 – Force–drift curve in monotonic tests of flattened types and analytical model – welded connections



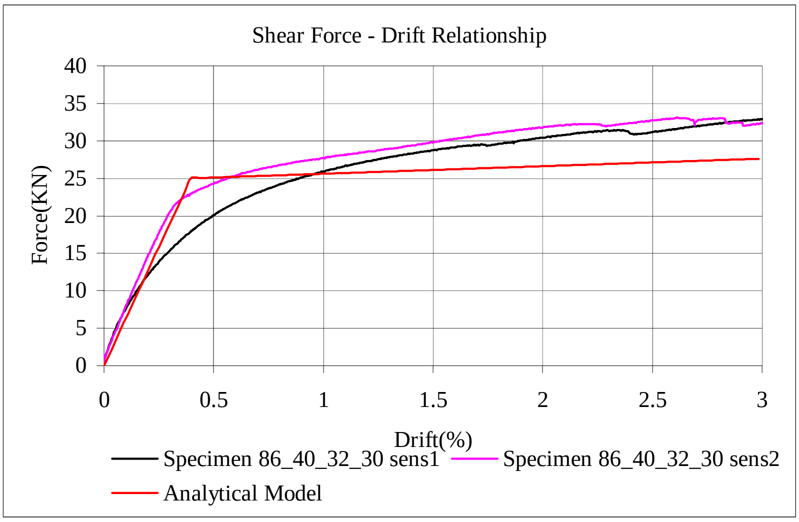


Figure -23 – Force–drift curves in monotonic tests of normal types and analytical model – welded connections

Table -6 – Monotonic test results in small scale – welded connection specimens

Specimens	Yield force (KN)	Yield displacement (mm)	Yield Drift (%)	Initial Stiffness (KN/mm)	Ultimate shear force (KN)	Ultimate displacement (mm)	Ultimate Drift (%)
1	33.4	1.0	0.14	33.4	78.9	9.4	1.35
2	32.2	1.0	0.14	32.2	83.7	8.7	1.25
3	27.9	0.85	0.12	32.8	60.8	7.1	1.02
4	25.9	1.17	0.17	22.1	65.0	8.3	1.2
5	27.3	1.3	0.18	21.0	60.6	25.7	3.7
6	18.0	0.9	0.13	20.0	57.5	20.3	2.9
7	9.3	0.93	0.13	10.0	31.3	15.6	2.24
8	10.2	0.93	0.13	11.0	32.3	15.7	2.26

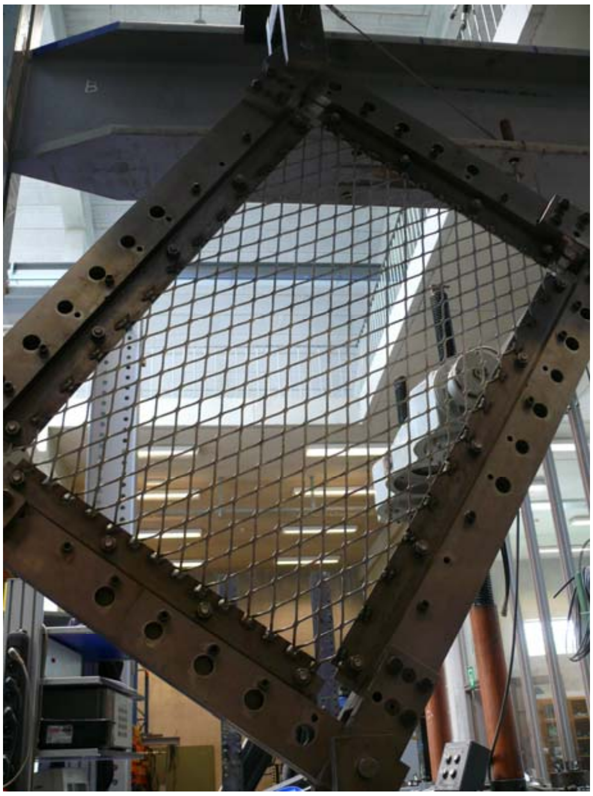


Figure -24 – Global view of the specimen A86_46_43_30 sens2 before testing

Figure -25 – Broken bars appeared in the monotonic test of specimen A51_27_35_30 sens2

I.4.2.2 Cyclic test phase

It should be recalled that there are two series of cyclic tests in small scale, which are distinguished by the differences of the connections between EMSP and testing frame. One uses welded connections with the overall dimensions of EMSP about 695mmx1095mm but the effective dimensions of rectangular EMSP only about 660mmx1056mm, and the other uses glue-epoxy connections with the bounding dimensions of EMSP about 695mmx1095mm but the effective dimensions of rectangular

EMSP only about 516mmx916mm. Apparently, although two series of tests share the same testing frame, which has the dimensions of 1000mmx1400mm, and have the same overall dimensions of small EMPS, however, the effective dimensions of EMSP in welded connections and glue connections are 660mmx1056mm and 516mmx916mm, respectively. There are eight specimens for a series of tests.

General features:

All specimens in both series of tests behave elastically in first four cycles until reaching a yield displacement which is also nearly the same as the yield displacements in monotonic tests. In the elastic range, the behaviour of all specimens is not completely symmetric. The reasons for this physical phenomenon are that there always exist initial deformations of small EMSP specimens leading to some initial stress, and moreover because the controlled displacements of EMSP in this stage are very small, displacements from the jacks and of the EMSP are much different. Beyond elastic ranges when the displacements become larger the hysteric loops are more symmetric.

Initial out of plane deformations are visibly observed in most of EMSP specimens before testing. These deformations are unavoidable because of very thin sheets. In addition, it is impossible to constantly keep EMSP specimens absolutely flat during fabricating processes, especially on specimens of welded connections. In some specimens such as A51_27_35_30 sens 1 and sens 2, 51_23_32_30 sens 1and sens 2, these phenomena become clearer after low shear forces are applied to the sheets. Out of plane deflections of the sheets are larger in successive cycles.

In all monotonic tests, there is no instability of individual bar. The same states of the bars are also observed in first four cycles in quasi-static cyclic tests. However, when reaching to yield displacements and up to the appearances of first broken bars, instability phenomena of bars are clearly observed in all specimens. In addition, the section areas of all the buckled bars are reduced visibly.

Like in monotonic tests, all first broken bars, as shown in Figure -26, are located at four corners of the testing frame, and before being broken their section areas are considerably reduced. It is also observed that the crack directions in all cyclic tests start at four corners and then progress to the centre of the sheets to form four crack lines. It is worth noting that, in almost all cyclic tests, the maximum shear force is attained on the cycle on which the first broken bars have appeared.

During first four cycles of both test series, the behaviour of the small EMSP specimens seems linear. From fifth cycle to the end of the tests the shapes of hysteretic behaviour of the small EMSP specimens are stable S-shapes. Hysteretic loops in all specimens are characterized by strong pinching. Pinching effects are due to the global instabilities of the small EMSP specimens, which cause large degradation in stiffness of the sheets. Like in monotonic tests, tension bands are developed in sheets in every cycle. In addition, because of the pinching effects, before redeveloping new tension band the stiffness of the sheets is approximately equal to zero in the other diagonal.

From the beginning to the end of the tests, there has been no failure either at the welded connections or glue-epoxy connections between the expanded metal sheets and the testing frame. It is also observed that there is no failure on the testing frame.

Particular features:

In monotonic tests, if two specimens have the same profiles but they are different in the way of setting up to the testing frame, their behaviour is not much different. In cyclic tests, their behaviour is very similar in first four cycles. It means that in these cycles, the sheets are in elastic ranges. However, in the plastic range, particularly when reaching the ultimate shear forces or the maximum displacements which are corresponding to ultimate shear forces in monotonic tests, some specimens behave quite differently. The ultimate shear forces and number of hysteretic cycles are quite different from one specimen to another.

Table -8 – First four cycle results of specimens with glue connections

Specimens	Forces at fourth cycle (KN)	Displacements at fourth cycle (mm)	Drift at fourth cycle (%)
9 – glue connections	39,4	0,80	0,15
10 – glue connections	36,0	1,1	0,22
11 – glue connections	49,0	0,8	0,15
12 – glue connections	43,9	1,2	0,22
13 – glue connections	42,7	1,2	0,22
14 – glue connections	24	1,76	0,34
15 – glue connections	20,2	1,4	0,31

Table -9, Table -10 and Table -10, the number of cycles in hysteretic behaviour of flattened expanded metal types and the energy which is dissipated are greater than that of normal types. It is also observed that out of plane deformations at failure of normal type specimens are much greater than those of flattened specimens. As shown in Figure -27 and Figure -28, pinching effects on the hysteretic behaviour are much larger in normal type specimens than in flattened type specimens.

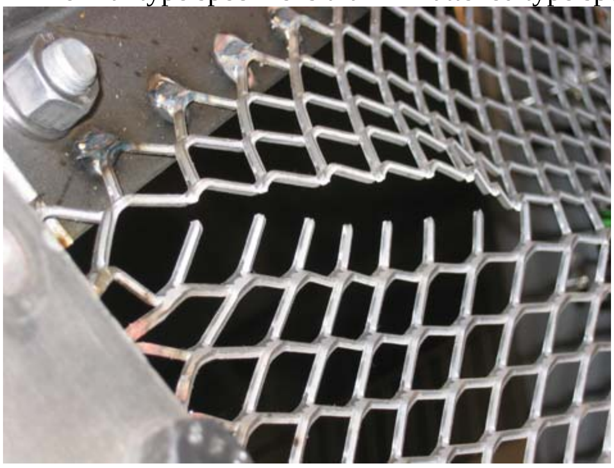


Figure -26 – Crack line and broken bars

Table -7 – First four cycle results of specimens with welded connections

Specimens	Monotonic yield force (KN)	Monotonic yield displacement (mm)	Monotonic yield Drift (%)	Forces at fourth cycle (KN)	Displacements at fourth cycle (mm)	Drift at fourth cycle (%)
1 – welded connections	33,4	1,0	0,14	30,4	1,01	0,15
2 – welded connections	32,2	1,0	0,14	31,1	1,02	0,15
3 – welded connections	27,9	0,85	0,12	20,2	0,88	0,13
4 – welded connections	25,9	1,17	0,17	24	1,10	0,15
5 – welded connections	27,3	1,3	0,18	23,4	1,01	0,15
6 – welded connections	18,0	0,9	0,13	19,0	1,00	0,15
7 – welded connections	9,3	0,93	0,13	10,1	1,20	0,17
8 – welded connections	10,2	0,93	0,13	11,0	1,29	0,19

Table -8 – First four cycle results of specimens with glue connections

Specimens	Forces at fourth cycle (KN)	Displacements at fourth cycle (mm)	Drift at fourth cycle (%)
9 – glue connections	39,4	0,80	0,15
10 – glue connections	36,0	1,1	0,22
11 – glue connections	49,0	0,8	0,15
12 – glue connections	43,9	1,2	0,22
13 – glue connections	42,7	1,2	0,22
14 – glue connections	24	1,76	0,34
15 – glue connections	20,2	1,4	0,31

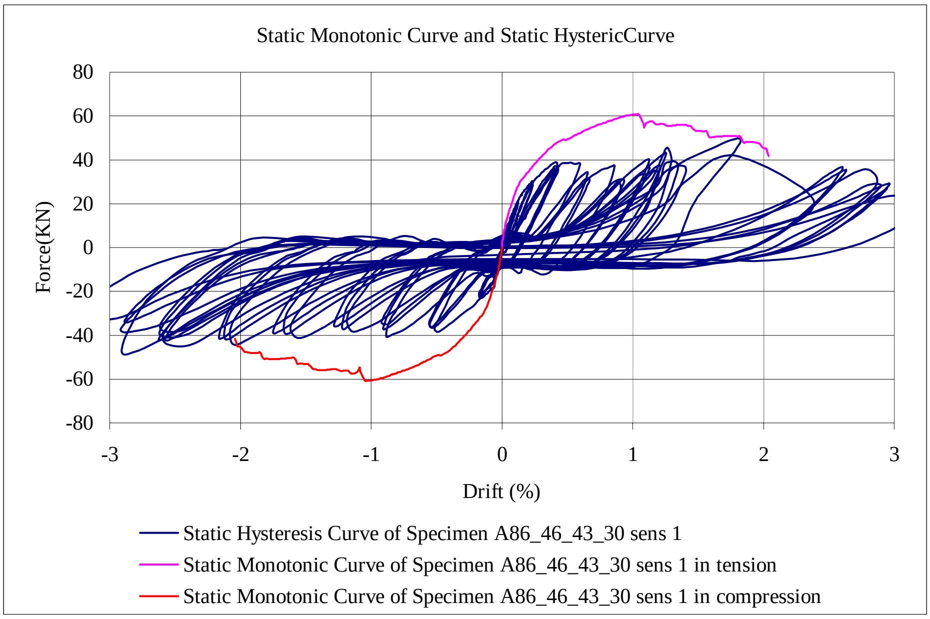
Table -9 – Cyclic testing results at displacements corresponding to ultimate forces in monotonic tests

Specimens	Monotonic ultimate shear force (KN)	Corresp. Displacement (mm)	Corresp. Drift (%)	Corresp. Shear force (KN)	Displacements at corresponding monotonic test (mm)	Corresp. drift (%)	Number of cycles (cycles)
1 – welded connections	78.9	9.4	1.35	56.0	9.8	1.41	23
2 – welded connections	83.7	8.7	1.25	74.0	9.7	1.40	14
3 – welded connections	60.8	7.1	1.02	42.5	8.7	1.30	20
4 – welded connections	65.0	8.3	1.2	43.3	9.3	1.34	11
5 – welded connections	60.6	25.7	3.7	15.5	20.9	3.0	32
6 – welded connections	57.5	20.3	2.9	40.5	20.4	3.0	12
7 – welded connections	31.3	15.6	2.24	23.2	14.5	2.1	11
8 – welded connections	32.3	15.7	2.26	28.9	14.5	2.1	14

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

Specimens	Cyclic ultimate shear forces (KN)	Cyclic corresponding displacements (mm)	Cyclic corresponding drifts (%)	Number of cycles (cycles)
1 – welded connections	71.6	8.3	1.2	20
2 – welded connections	-75.6	-16.9	2.4	16
3 – welded connections	-48.2	-20.2	2.9	26
4 – welded connections	-49.3	-14.8	2.1	13
5 – welded connections	-48	-7.3	1.1	14
6 – welded connections	-45	-7	1.0	10
7 – welded connections	27	9.3	1.33	8
8 – welded connections	-28	-10.8	1.56	12
9 – glue connections	77,2	4,5	0,8	11
10 – glue connections	90,5	5,7	1,1	11
11 – glue connections	66,2	4,2	0,99	11
12 – glue connections	54,4	7,1	1,4	11
13 – glue connections	51	6,1	1,14	8
14 – glue connections	30,7	8,3	1,6	8

15 – glue connections	31,1	6,0	1,2	8



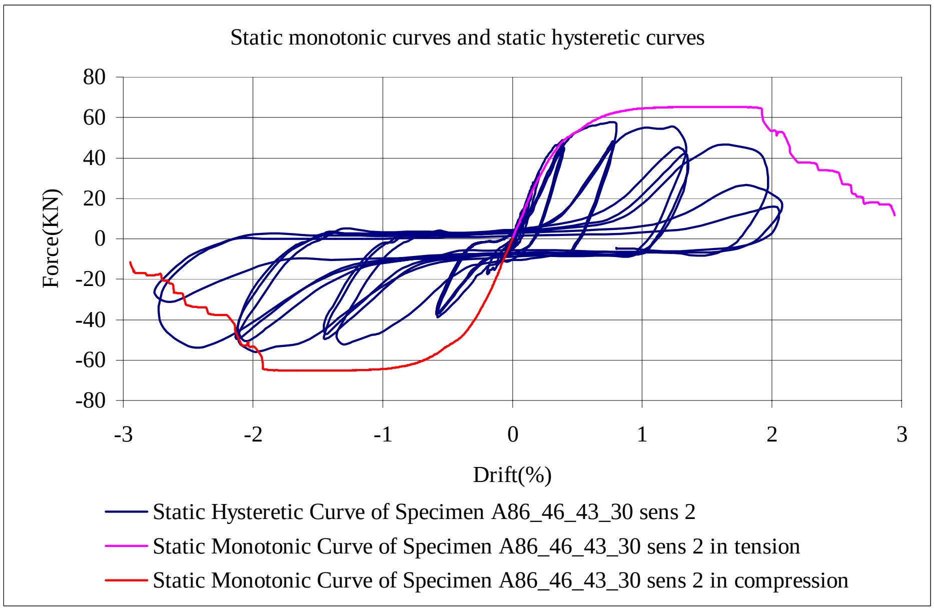
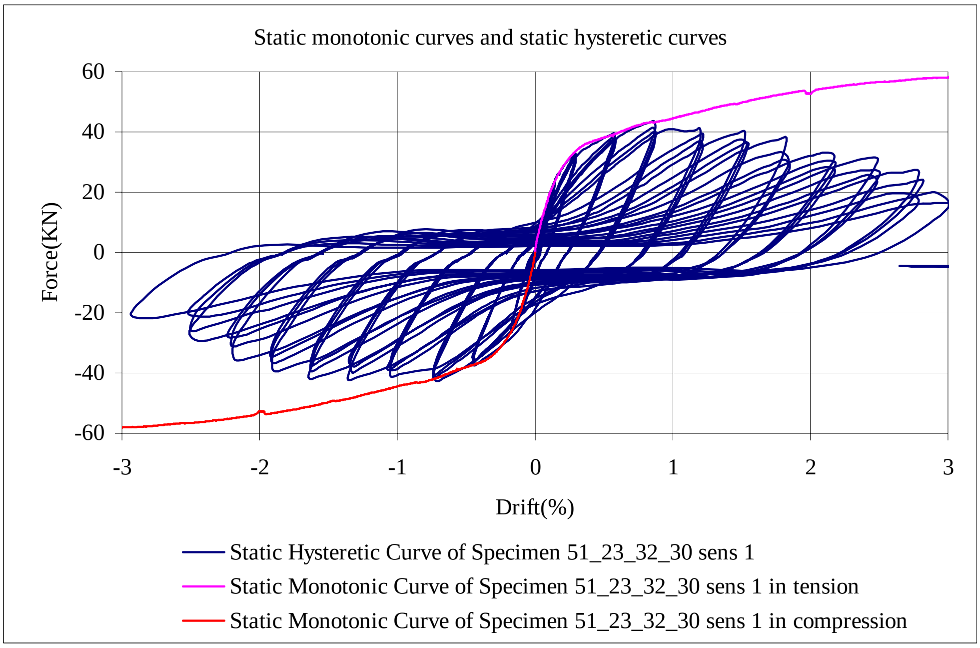


Figure -27 – Hysteretic behaviour of flattened type specimens – welded connections



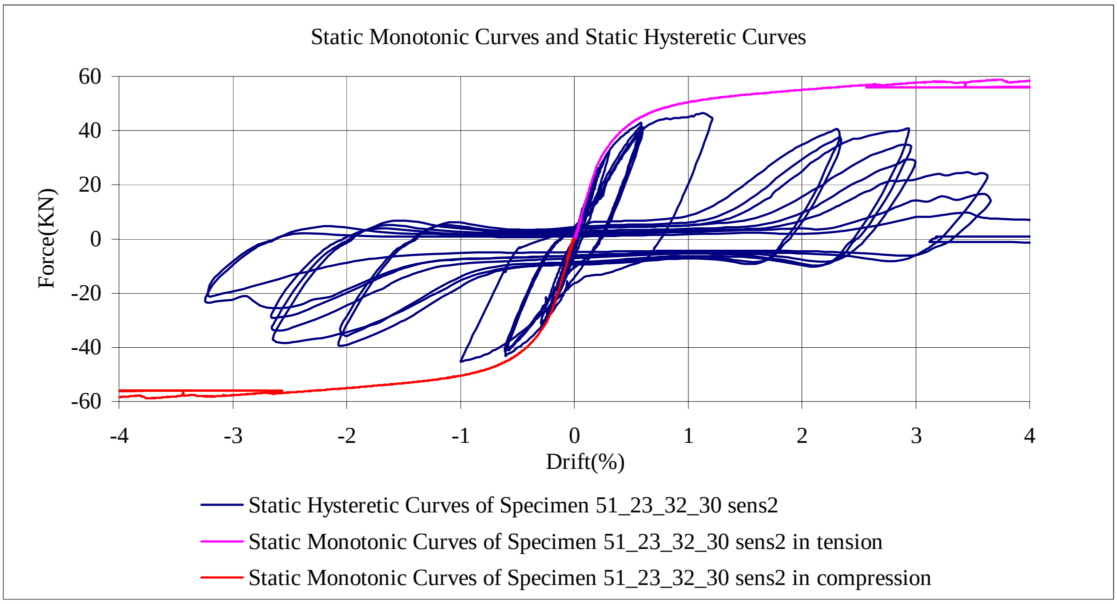
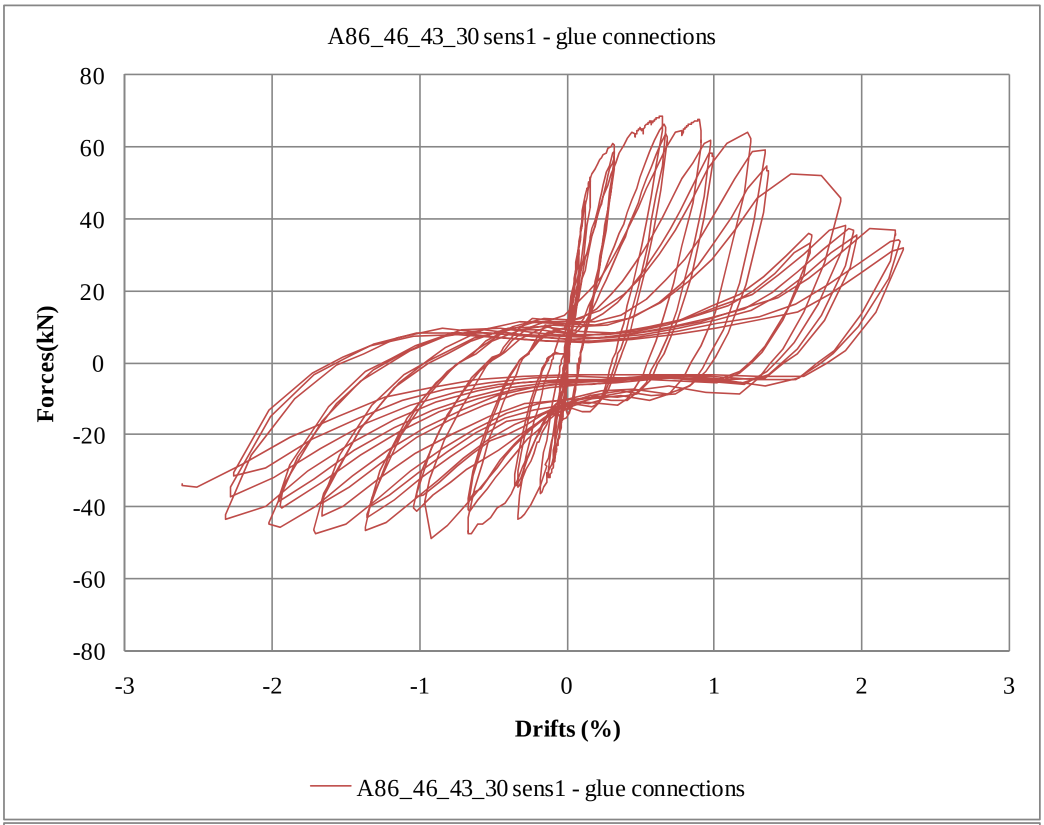


Figure -28 – Hysteretic behaviour of normal type specimens – welded connections



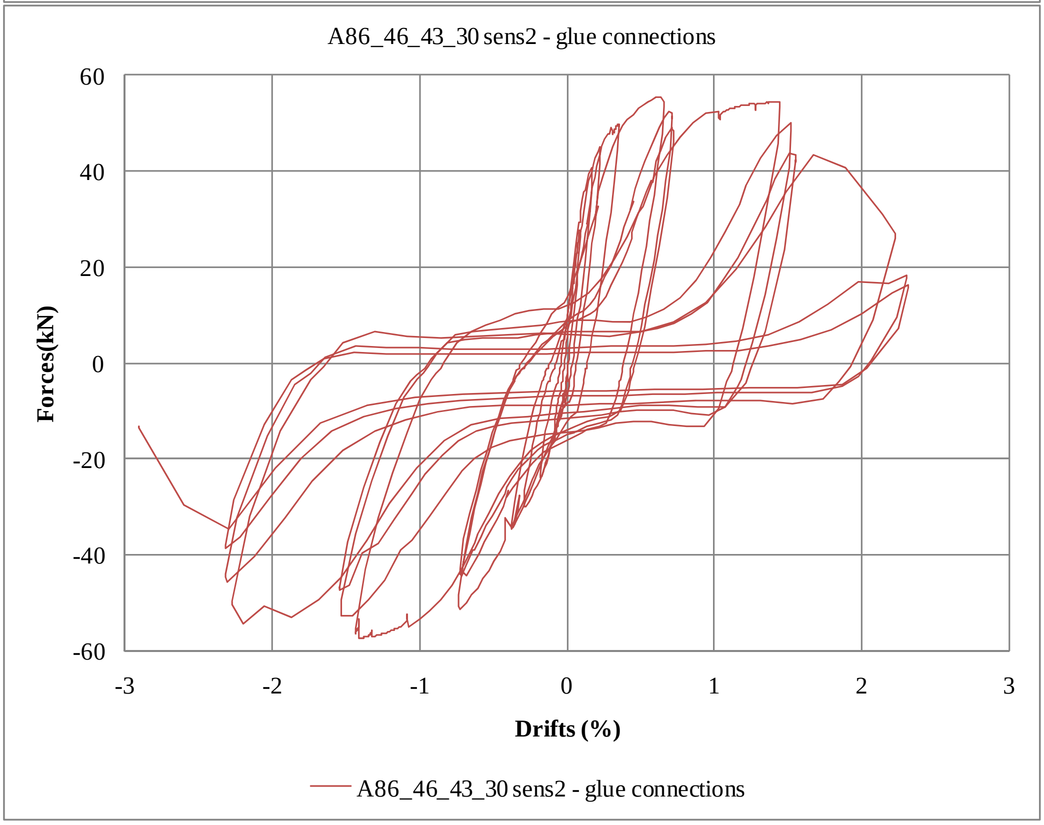
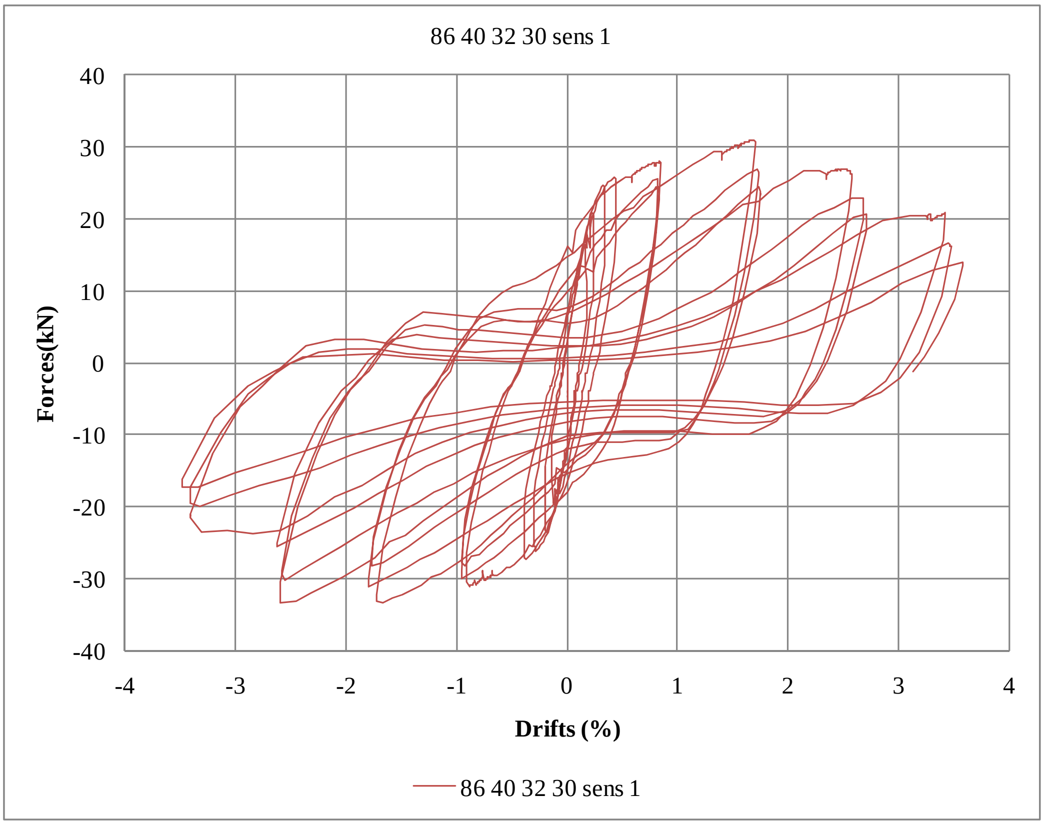


Figure -29 – Hysteretic behaviour of flattened type specimens – glue connections



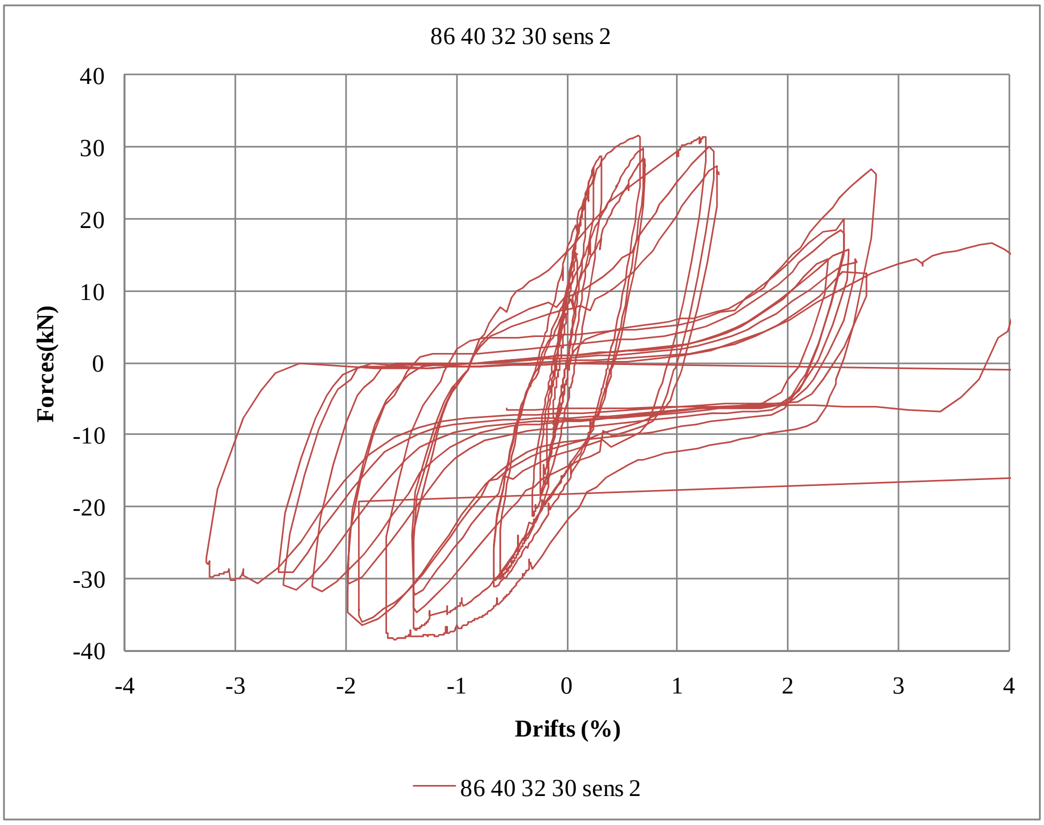


Figure -30 – Hysteretic behaviour of normal type specimens – glue connections

I.4.3 Tests in large scale

I.4.3.1 Monotonic loading phase

As well as the tests in small scale, monotonic tests are carried out with the aims at determining the parameters for quasi-static and dynamic tests, at assessing the ductility of EMSP and at comparing with numerical simulations of testing specimens. There are two tests in monotonic phases corresponding to two products of flattened MD: A51_27_35_30 and A86_46_43_30.

General features:
In both specimens, before testing the out of plane deformations are clearly observed. The initial out of plane deflection of the specimen A86_46_43_30 is greater than that of the specimen A51_27_35_30. It can deduce that the larger voids of EMSP, the bigger out of plane deformations are. These deformations become much clearer when applying very low shear loads. All of these physical phenomena are similar to those of tests in small scale. However, the buckling shapes of EMSP are quite different, as clearly observed in Figure -21 and Figure -31. This is because two sheets of EMSP panels are connected together by using a very stiff T-shape steel plate. With the presence of very stiff plates at the middle of EMSP, as shown in Figure -10, it will more or less prevent EMSP from being buckled, and two sheets of EMSP will be buckled individually.
As observed from the beginning to the end of all tests, the behaviour of two specimens is almost like the monotonic tests of small scale. It can also be divided into two ranges: nonlinear elastic and nonlinear plastic ranges. The yielding points of the tests cannot be clearly defined. Based on the instruction of ECCS 1986 [R3.10], two stiffness tangents of load-displacement relationships are located, and conventional yielding displacements and yielding loads are approximately determined. It is worth noting that both elastic and plastic behaviour of the specimens are nonlinear. Table -11 summarises all considering properties of the tests. The yielding forces of two tests of A51_27_35_30 and A86_46_43_30 are 140kN and 90kN in order. The yielding displacements of these two tests are 23mm (0,9%) and 23,6mm (0,99%), respectively.
Although yielding properties of tested EMSP are not easily determined, however, ultimate shear loads and corresponding transversal displacements of EMSP are easier observed. After reaching to ultimate shear forces, it can be seen that the stiffness and strength of two specimens decrease a lot. Regardless of the large degradation in stiffness and strength, the displacements of the EMSP are still increased until reaching maximum displacements, which are about three to five times greater than yielding displacements. The shear loads, which correspond to maximum displacements, are about 65% of ultimate loads.

Figure -31 – Global buckling shapes of two sheets of the EMSP panel

Table -11 – Monotonic test results in large scale

Specimens	Yield force (KN)	Yield displacement (mm)	Yield Drift (%)	Ultimate shear force (KN)	Ultimate displacement (mm)	Ultimate Drift (%)
1 – A51_27_35_30	140	23	0,9	190,4	47,8	1,9
2 – A86_46_43_30	90	23,6	0,99	111,1	35,3	1,5

The first broken bars observed in all monotonic tests are located at the two corners of the two sheets of testing EMSP, which are right-lower corner of the specimen A51_27_35_30 and left-upper corner of the specimen A86_46_43_30. These phenomena are the same as tests in small scale. In addition, the section areas of these bars, which are in tension, are clearly decreased before being broken. Similarly to the tests in small scale, in spite of the fact that some bars are broken, the testing EMSP still keep carrying shear forces until failures. It is also observed that after each bar is broken the shear force is suddenly reduced and then increased until the sheets are completely broken. In addition, the broken bars first appear at the corners of the testing EMSP, and then spread gradually to the centre of the sheets. As in small monotonic tests, though the EMSP is prone to global buckling, but no buckle of individual bar is observed from the beginning to the end of the test.

All the tests are stopped because small EMSP specimens have been largely deformed, and almost tensile strips are broken, as shown in Figure -32. At failures, large out of plane deformations in both specimens are clearly observed. There is no failure either at the weld connections between the expanded metal sheets and the plates or at the bolt connections between sheet-plates and intermediate-plates.

Figure -32 – Broken bars in monotonic large scale tests

Particular features

Specimen 1 - A51_27_35_30: Before setting up the specimen to the testing frame, it is easy to observe that there are some out of plane deformations. These deformations are present on the sheet because of welding connections between expanded metal sheet and the gussets. At the beginning of the test, corresponding to the very small values of displacements and shear forces (less than 23mm – 0,9% drift and 140 kN), the behaviour of the specimen is mainly elastic. Moreover, at this initial part of the test, it is clearly observed that global instability of the sheet has appeared with buckling waves. These waves are parallel to tension diagonal. After global buckling, the applied forces and displacements are being increased and the sheet develops a visible tension diagonal field until the specimen is completely broken. There are some broken bars which can be seen at the opposite diagonal corner to the tension field. The section areas of these bars are clearly decreased before being broken. After each bar is broken, the shear force is suddenly reduced. Although there are some discrete broken bars appeared at the opposite corners of tension field, however, at the ultimate load, the sheet is completely broken with the cracks along the diagonal. The EMSP is totally ruptured at the force of 190,4KN and the displacement of 47,8mm (1.9% drift). As expected, there is no broken neither at the welding between the sheet and the gussets nor at the bolt connections between the sheet and the frame. Figure -33 shows a view of the EMSP after the test. Figure -34 shows the static relationship between force and drift of the specimen.

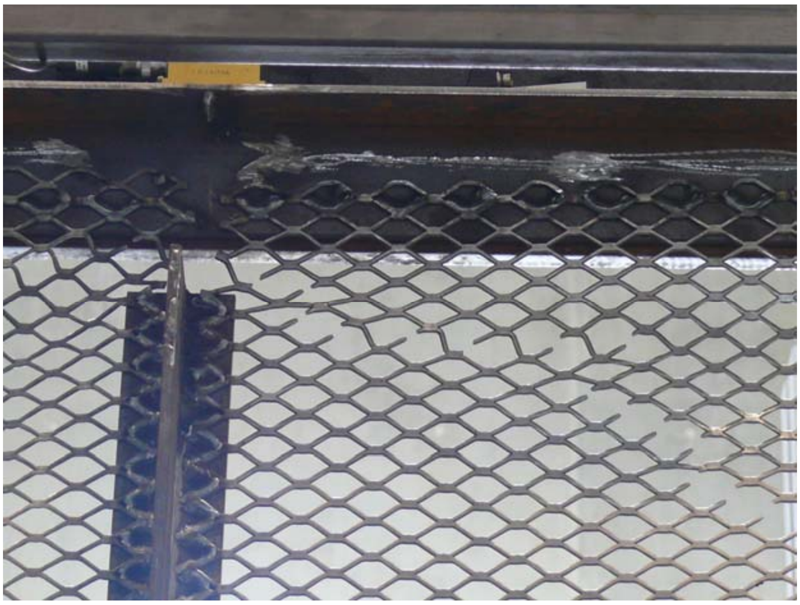


Figure -33 – Broken bars of EMSP at failures

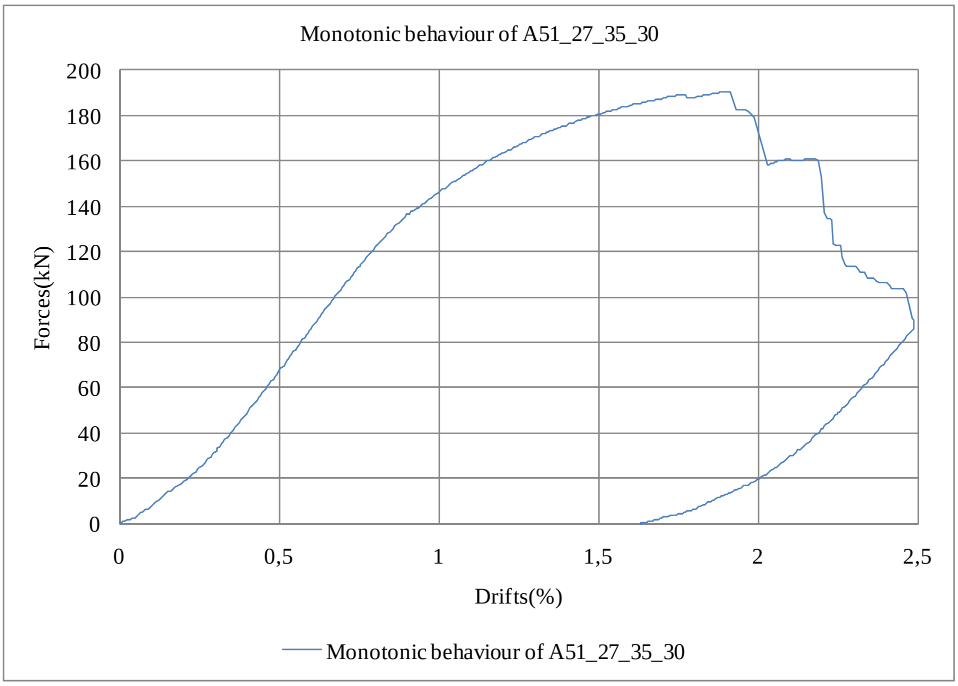


Figure -34 – Monotonic behaviour of specimen 1 – A51_27_35_30

Specimen2 – A86_46_43_30: Because the voids of this specimen sheet are large, one can easily observe the out of plane deformation of the sheet before erecting the sheet to the testing frame. These initial deformations of the specimen are discretely distributed because of welding between the sheet and gussets. Up to the displacement value of 23,6mm (0.99% drift), the sheet behaved almost elastically and the corresponding force was of 90kN. Furthermore, the EMSP is globally buckled at the very low shear force. The buckling waves aree along the diagonal at which force applied. At the end of the test, the large out of plane deformation is observed. Before being completely broken, many broken bars are observed and their sectional areas are largely reduced. The ultimate shear force and displacement are of 111,1kN and 35,3mm (1.5% drift), respectively. The test is stopped because of large degradation in strength of the specimen. Test is terminated when the drift approximately reached to 2% and the shear force is reduced to 60kN. Figure -35 shows global instability of specimen. Figure -36 shows relationship between force and drift of the specimen.

Figure -35 – Global instability of the specimen

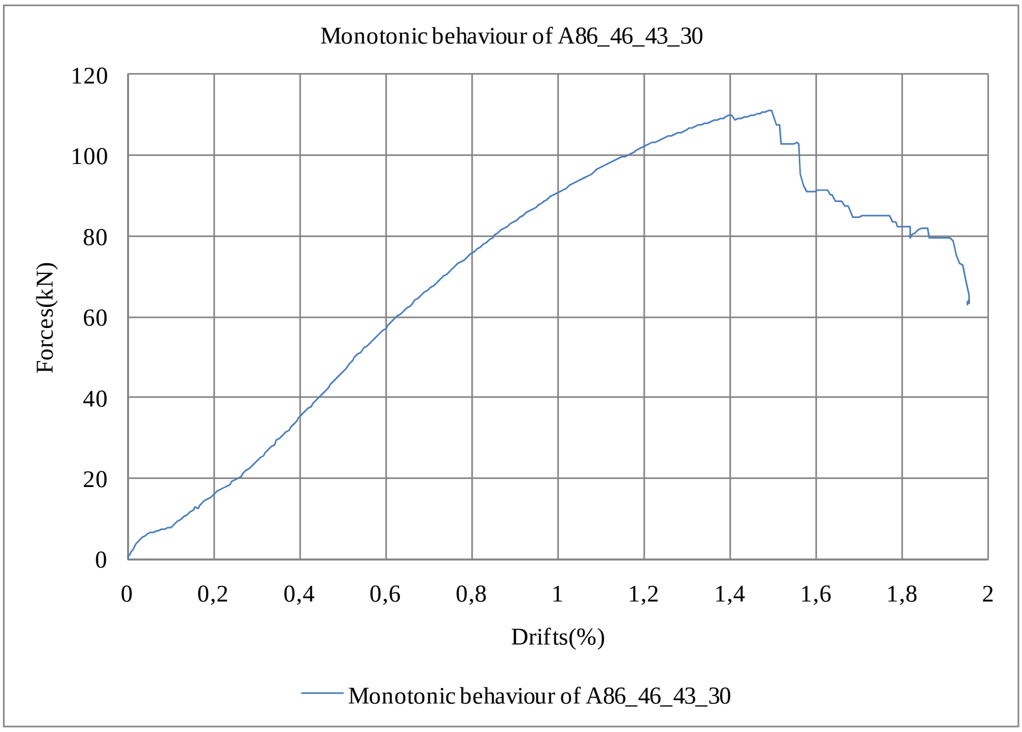


Figure -36 – Monotonic behaviour in large scale tests

I.4.3.2 Cyclic loading phase

General features:

All specimens in both tests behave elastically in first four cycles until reaching a yield displacement which is also nearly the same as the yield displacements in monotonic tests. In the elastic range, the behaviour of all specimens is not completely symmetric. The reasons for this physical phenomenon are that there always exist initial deformations of small EMSP specimens leading to some initial stress. Beyond elastic ranges when the displacements become larger the hysteric loops are more symmetric.

Initial out of plane deformations are visibly observed in most of EMSP specimens before testing. These deformations are unavoidable because of very thin sheets. In addition, it is impossible to constantly keep EMSP specimens absolutely flat during fabricating processes, especially on specimens of welded connections. In specimen 1, that is, A51_27_35_30, this phenomenon becomes clearer after low shear forces are applied to the sheets. Out of plane deflections of the sheets are larger in successive cycles.

In all monotonic tests, there is no instability of individual bar. The same states of the bars are also observed in first four cycles in quasi-static cyclic tests. However, when reaching to yield displacements and up to the appearances of first broken bars, instability phenomena of bars are clearly observed in all specimens. In addition, the section areas of all the buckled bars are reduced visibly.

Like in monotonic tests, all first broken bars, as shown in Figure -37 – Broken bars of the sheets in EMSP specimen Figure -37, are located at four corners of the testing frame, and before being broken their section areas are considerably reduced. It is also observed that the crack directions in all cyclic tests start at four corners and then progress to the centre of the sheets to form four crack lines. It is worth noting that, in almost all cyclic tests, the maximum shear force is attained on the cycle on which the first broken bars have appeared.

During first four cycles of both tests, the behaviour of the small EMSP specimens seems linear. From fifth cycle to the end of the tests the shapes of hysteretic behaviour of the small EMSP specimens are stable S-shapes. Hysteretic loops in all specimens are characterized by strong pinching. Pinching effects are due to the global instabilities of the small EMSP specimens, which cause large degradation in stiffness of the sheets. Like in monotonic tests, tension bands are developed in sheets in every cycle. In addition, because of the pinching effects, before redeveloping new tension band the stiffness of the sheets is approximately equal to zero in the other diagonal. From the beginning to the end of the tests, there has been no failure either at the welded connections between the expanded metal sheets and the testing frame. It is also observed that there is no failure on the testing frame. Table -12, Table -13 and Table -14 present the results of the tests in large scale.

Figure -37 – Broken bars of the sheets in EMSP specimen

Table -12 – First four cycle results of specimens with welded connections

Specimens	Monotonic yield force (KN)	Monotonic yield displacement (mm)	Monotonic yield Drift (%)	Forces at yielding (KN)	Displacements at yielding (mm)	Drift at yielding cycle (%)
1 – welded connections	140	23	0,9	140,7	22,4	0,89
2 – welded connections	90	23,6	0,99	93,4	23,1	0,97

Table -13 – Cyclic results at displacements corresponding to ultimate forces in monotonic tests

Specimens	Monotonic ultimate shear force (KN)	Corresponding displacement (mm)	Corresponding drift (%)	Corresponding shear force (KN)	Displacements at relatively corresponding to monotonic test (mm)	Corresponding drift (%)	Number of cycles (cycles)
1 – welded connections	190,4	47,8	1,9	195	42,4	1,8	8
2 – welded connections	111,1	35,3	1,5	109	35,4	1,51	8

Table -14 – Maximum shear forces in cyclic tests and corresponding displacements

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

Particular features:

Specimen 3 - A51_27_35_30: The behaviour of this specimen in first four cycles seemed elastic. It is easy to observe that force-displacement relationship at these cycles is not symmetric. At first haft of fourth cycle, when the displacement is up to the value of -3,45mm (0.14% drift) the corresponding shear force was of 23,4kN, but when the displacement is of +3,2mm (0,13% drift), the corresponding shear force is just only of 12,3kN. In next cycles, the loops became more symmetric. From the fifth cycle, within a group of three successive cycles without changing in target displacements, one can clearly observe that there are the stiffness degradations of the sheet. After first four cycles, global instabilities of the specimen become more clearly. And when the sheet is completely broken, the out of plane deformations are much larger than monotonic test. The first broken bar is at the down-left corner of the EMSP. After having appeared the first broken bar, the forces acting on the sheet still increased in next cycles until reaching the ultimate values. It is also observed that before being broken, section of the bar is reduced, and that bar is apparently buckled. It is worth noticing that the cracks of the sheet until complete failure almost develop from four corners of the sheets of EMSP specimen. In addition, from the fifth cycle, before changing the directions of loading, one can observe the rapid increasing of displacement, and the stiffness of the EMSP is approximately equal to zero. Figure -38 shows the hysteretic curves between force and drift comparing with monotonic curve.

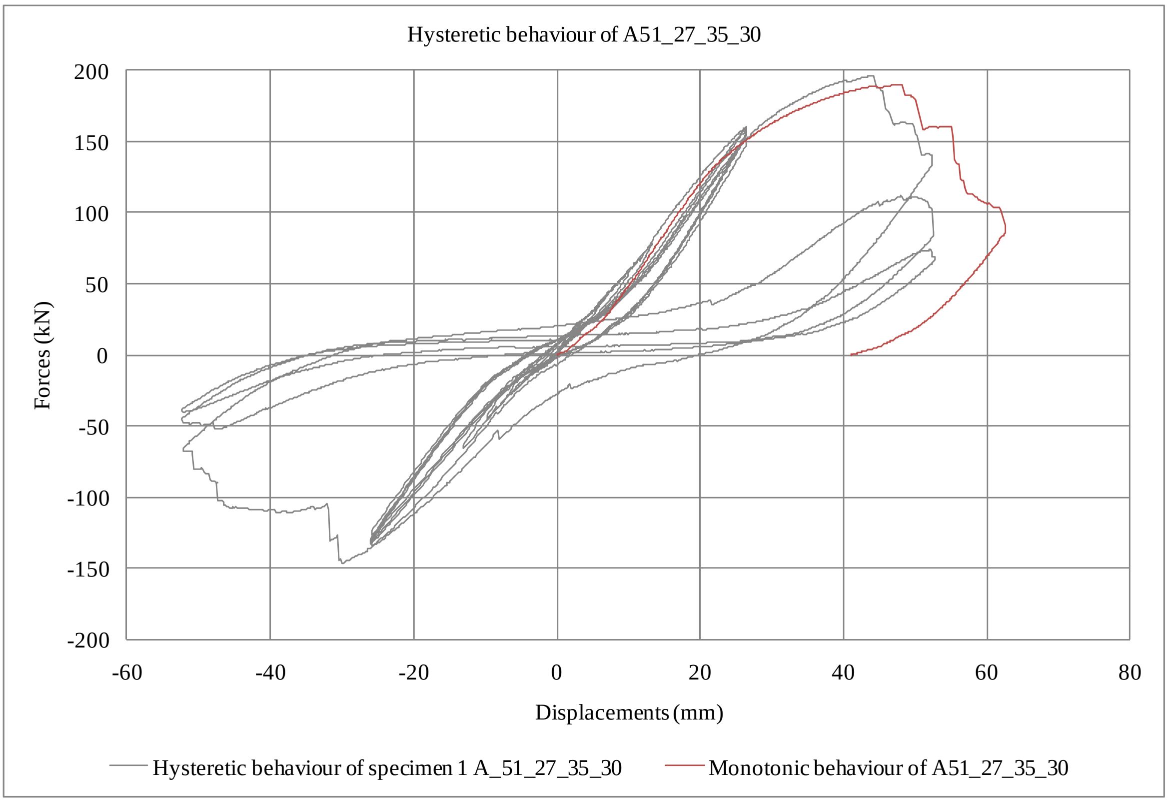


Figure -38 – Hysteretic behaviour of the specimen A51_27_35_30

Specimen 4 – A86_46_43_30: Specimen 4 exhibits linear behaviour during the first four cycles. Global buckling begins to occur from the beginning of the test and progresses in subsequent cycles. At the first haft of cycle 5, the magnitude of the buckling waves becomes more visible. The first broken bar is locally buckled. After this cycle, the global deformations of the sheet increased quickly. Besides global instability can be easily observed, local buckling of some bars is also observed. Until having reached to complete failure, it is clearly observed that the fractures of the sheet are developed along the diagonals of sheets of EMSP. The specimen is successfully tested to 64mm ($4e_y$, 2.5% drift). The maximum shear force in tension was of 111,1KN which occurred at $2e_y$ – 1,25% drift. The test was stopped at cycle 8 because the force is reduced to 30kN and corresponding displacement is 72mm. Figure -39 shows the relationship between forces and drifts of hysteretic and monotonic behaviour.

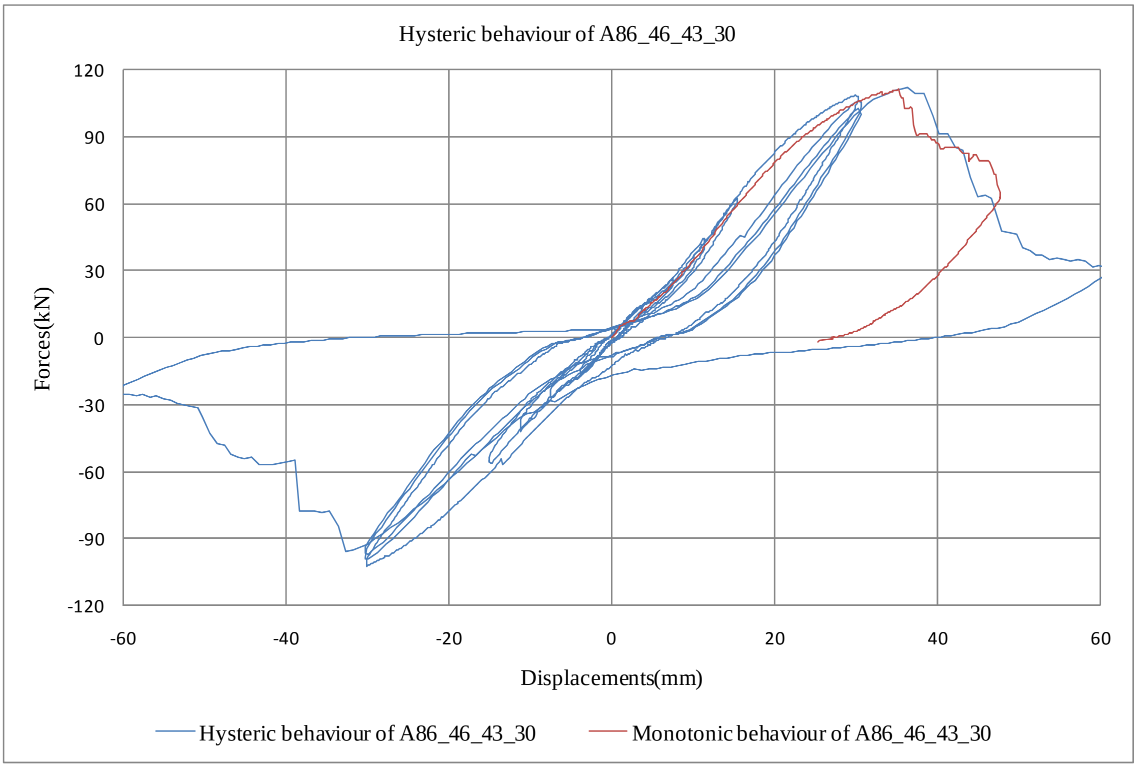


Figure -39 – Hysteretic behaviour of the specimen A86_46_43_30

I.5 Summary of observations and conclusions

1. An experimental test program has been carried out on small scale and large scale of un-stiffened expanded metal sheet test specimens. The main objectives of the tests is to calibrate the simple analytical model for monotonic shear loading that has been proposed by Etienne Pecquet [2] and to study the hysteretic behaviour of expanded metal sheets subjected to shear.

2. The correlation between the analytical model and monotonic tests varies largely differently. In some cases, the analytical model much underestimates the real behaviour of the small EMSP specimens. It may be that only one tension band for the monotonic behaviour of the sheets is not enough. The sheets might work in more than one tension band.

3. Because under rather low shear forces the sheets are globally buckled, the contribution of compression diagonal to the resistance of sheets can be completely neglected.

4. The degradation in stiffness of the sheets due to pinching effects results in a smaller enclosed area under the hysteretic curve and, therefore, a lower amount of energy absorbed by the system during successive cycles.

5. The deflection required to redevelop the tension field is based on the yielding displacements experienced by the sheets on the previous cycles.

6. In both monotonic and cyclic phases of the tests all sheets have buckled at very low shear forces. Some of the specimens (specimens 7 and 8in small scale, and specimen 2 in large scale) were globally buckled before testing. Furthermore it was observed that normal types of small EMSP specimens, including specimen 5, 6, 7 and 8 (profiles: 51_23_32_30 and 86_40_32_30), buckle more easily than flattened types, which are specimens 1, 2, 3 and 4 (profiles: A51_27_35_30 and A86_46_43_30).

7. 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. Besides there is no bar being locally buckled in monotonic tests. However, in all cyclic tests, many bars have been buckled before being broken. Moreover, in almost cyclic tests, the maximum shear forces have been attained on the cycle on which first broken bar has been observed.

8. The maximum shear forces of small EMSP 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.

9. 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 due to yielding in tension and to buckling in compression caused the degradation of stiffness of the sheets. In cyclic tests, pinching effects are clear in successive cycles beyond the elastic range. In addition, the magnitude of the buckling deformations and deterioration in stiffness of sheets are increased correspondingly.

10. In all specimens in cyclic test phases, the stiffness of the sheets is approximately equal to zero during the inversion of force.

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