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Structural analysis of a mobile device for the End–of–Life treatment of photovoltaic panels

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Abstract

The use of photovoltaic panels in Europe led to the installation of about 100GWp in the last decade, an amount which is still growing. The productive life of panels is expected to be between 10 to 30 years, so that in the future a strong demand for systems able to perform their End–of–Life treatment is undoubted. As a consequence of the Directive 2012/19/EU, the decommissioning of photovoltaic plants has to be performed in order to achieve challenging material recycling and recovery targets. Small size, mobile treatment plants have been proposed to reduce the investment needed for their installation in comparison with large industrial ones.

A prototype system for the treatment of photovoltaic panels is presented; it is designed to be transported within the limits of ordinary freight transport vehicles. All the systems included in the plant have been organized in a production line mounted in three containers. Due to functional reasons, the containers have been design and built specifically for these use, providing the necessary integration between the installed machinery and of auxiliary systems such as dust collection system, sound insulation and vibration absorbers. For the verification of resistance and stiffness of the system – which differs from regular freight containers – an adaptation of suitable standards is proposed. After the definition of appropriate loads for the case study, the structures of the containers are analyzed using Finite Elements software. The analysis shows that due to the characteristics of the application the structure is not suitable for general containers use, but – considering the limitations of the application in terms of transportation needs – the results can be considered acceptable.

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Keywords: Photovoltaics; WEEE; EOL; Container; Stiffness; Resistance; FEM.

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1. Introduction

The use of Photovoltaic (PV) panels led to the installation of about 100GWp in Europe and 220GWp Worldwide, an amount which is still growing; a rise up to 4500GWp in 2050 has been hypothesized. Their productive life is expected to be between 10 to 30 years, so that in the future a strong demand for systems able to perform their End–of–Life treatment is certain. In particular, the treated amount is estimated to be about 45.000–250.000t/y in the next years (before 2020), growing up to 75Mt/y in 2050 worldwide (Weckend et al., 2016). As a consequence of the Directive 2012/19/EU on Waste Electrical and Electronic Equipment – WEEE – (EC, 2012), in Europe the decommissioning of photovoltaic plants has to be performed in order to achieve challenging material recycling and recovery targets (expected to be more than 80% and 85% respectively). PV plants size is extremely various and can vary a few kWp for personal/home production (Cucchiella et al., 2016a) to MWp for large solar fields. Considering residential buildings roofs, car parking areas, factories a large number of small size systems have been installed, spread over rural, industrial and urban areas. For this reason, the collection chain of End–Of–Life (EoL) PV should be able to intercept all the flows, even if coming from areas characterized by a low level of industrialization. Treatment plants characterized by small capacity and treatment rate – in the range of a few tons per hour or even less – have been proposed in order to reduce the investment needed for their installation in comparison with large ones, a solution which is intended to enhance the availability of recycling plants over territories (Rocchetti et al., 2013; Zeng et al., 2015). The reduction of plant cost for WEEE treatment – also other than PVs – is a relevant topic due to uncertain profitability of treatment operations (Cucchiella et al., 2016b).

In this study, a prototype system for the treatment of photovoltaic panels is presented. The plant has been conceived and designed in order to be transported within the limits of ordinary freight transport vehicles. Due to this reason, all the systems included in the plant have been organized in a production line mounted in three containers. According to the necessities of the system, the containers have been design and built specifically for these use, providing the necessary integration between the installed machines and of auxiliary systems. Various studies are available in literature and some of them are focused on special uses of freight containers, such as special designed ones (Sepe et al., 2015) or on repurposing or conversion to static structures, for which multiple stacked elements are analysed (Giriunas et al., 2012; Zha and Zuo, 2016; Zuo and Zha, 2017). The objective of the present study is to examine a group of containers which differ from standardized ones for size and design concept. For such application, the use of standard resistance verification procedures for freight containers is not mandatory, since they are not supposed to be used together with other containers (e.g. stacked); as a consequence, the size of the plant containers has been chosen to be slightly different to standardized ones. Where possible, however, testing procedures applicable to similar containers (ISO, 1995, 2013a, 2013b) have been adopted; approval according to Directive 2006/42/EC and related regulations – also needed for the plant – is not part of this analysis (EC, 2006)

The article is structured as follows. In the next paragraph, the characteristics of the plant and of the units installed in the three containers are presented. Then, a selection of load cases is presented. Finally, the models of the structures are presented and the results of the analyses are shown.

2. Description of the plant and of its model

The treatment process of PV panels performed by the plant is aimed to reduce the panels in small parts in order to enable material recycling through proper segregation of different materials. Such process is quite typical for the treatment of EoL products, as described in literature (Granata et al., 2014; Pagnanelli et al., 2017; Rocchetti and Beolchini, 2015); the successful implementation of the process depends on those details which constitute the real know–how of the manufacturer of the system. Examples of such choices are: the use of a certain shredding process (e.g. fragmentation through hammer mills or shearing through other kind of machines) and of certain size for the particles; the installation of devices such as air classifiers and vibrating screens; the calibration of these machines, the speed of air flow etc.: each element installed in the system contribute to the successful implementation of material segregation processes. The plant under investigation is capable of processing about 0.8t/h.

2.1. Plant Layout

The PV panels mobile recycling device is composed by three containers; during operation, they have to be disposed in a single line, thus constituting a continuous treatment plant. Specific machines are installed in each container, while auxiliary systems (electrical supplies, dust removal and ventilation systems) are integrated in all of the three to ensure the correct operation of the device. The schematic layout is shown in Fig. 1. The process is constituted by three different fragmentation steps, each one followed by proper particle segregation through vibrating screens. Shredding is therefore performed at point 1 (PV Panel shearing device – this unit is built specifically for this use and is under patent), point 3 and 6 (hammers mills); the fragments are transported and segregated through vibrating screens (point 4, point 7 and point 9); dust and small fragments are aspirated by a distributed vacuum system, to be collected and treated at point 11. Conveyors are installed at point 2, 5 and 8. Other auxiliary systems (e.g. compressed air generator, point 12) are also located in the containers.

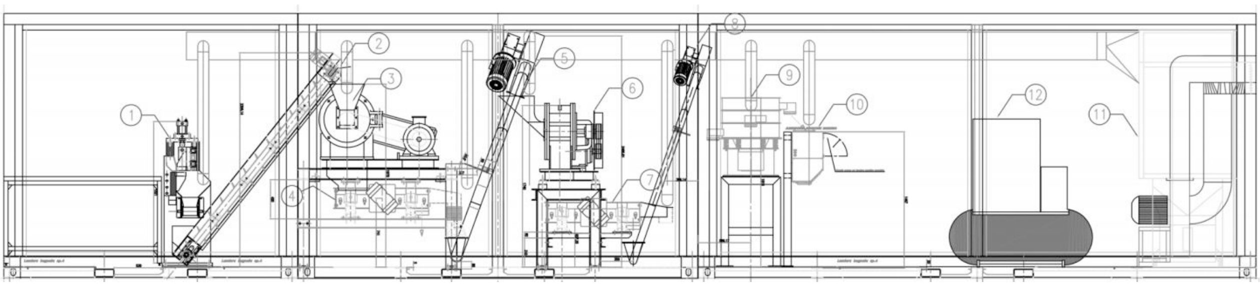


Fig. 1. Plant layout.

2.2. Structure of the containers

The containers as well as the frames inside used for equipment support have been built specifically for this application. In comparison with freight containers, the structures differ especially in the side and end walls, in the roof and in the floor components; this latter, in particular, is reinforced were needed to include the basement of the heavy machinery. Three different lengths characterize the containers. The first one, the longest placed at the end of panels treatment, measures 6˙000 mm; the second one, in central position, is 4˙300 mm long, and the last one (container 3) measures only 3˙160 mm (see Fig. 2).

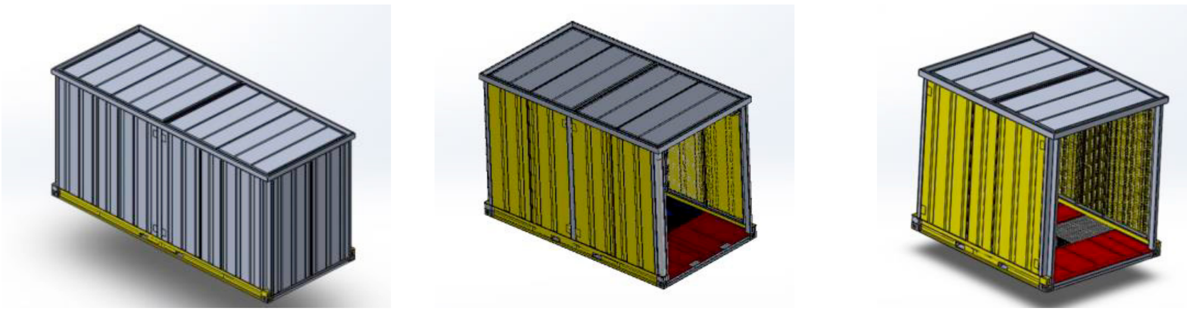


Fig. 2. Containers used for the plant.

Standard profiles have been used for structural parts. IPE 240 beams are used as bottom side rails; HEB 120 were used for cross members in transversal direction and bottom end rails. For container 3, two of the three cross members, are represented by UPN 120 beams of HEB 120. In longitudinal direction, square section bar with size 40x40 mm and thickness of 2.00 mm were used. Container corners are also specific: Fig. 3 (A) shows the corner posts realized with two sheets of 80x120x4 mm (pink) and 60x120x3 mm (orange). The yellow plate welded on the corner fitting (cyan) and on the bottom side rails (green) is used to connect the containers when the plant is operated. This is a peculiarity of those containers in comparison with freight ones. Walls were realized using metal sheets and embossed metal sheets for intrados and extrados respectively. The structure of the roof (see Fig. 3 (B)) consists of transversal C–profile (yellow), as structure, and metal panels as cover (grey). The C–profiles are welded on top side rails composed of rectangular extrusions of 60x80 mm (green) and another C–profile (green/yellow). The containers presented on this study are designed to have various doors and openings for maintenance of equipment and input/output operations of processed materials. The first container has two doors per side, only the rear end is closed and the front wall can be removed. The central container is open on both ends, to allow the access for workers from one container to another, and it presents two doors on each side. The last container, the smallest, has the same doors configuration of the central one. Door locking system uses light hinges so that it is assumed that there is no contribution to structural stiffness and resistance. Around the roof, an extruded element with specific section (red), is placed to harvest the rainwater. Another important feature is represented by the absence of the top corner casting. These containers were not designed for stacking, but only for lifting. In regard of this, the lifting from the top, is done using four special welded plates (orange) for shackles anchoring, one for each corner.

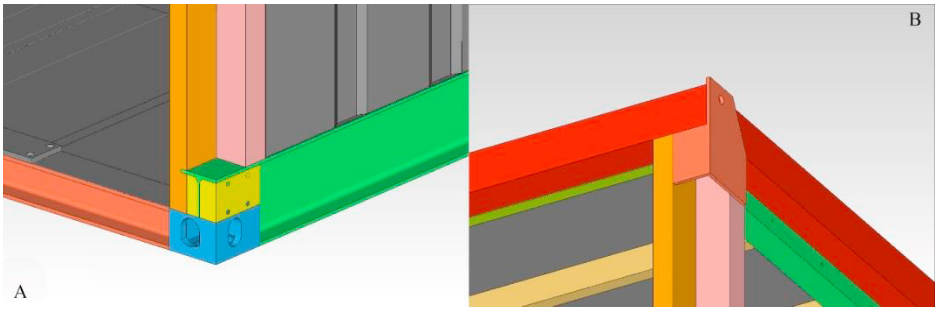


Fig. 3. Container components: bottom corner (A); top corner (B).

2.3. Plant model

The model of the containers is prepared using mostly two–dimensional elements. The models were simplified by removing all components having negligible mass, such as noise–absorbing panels, electrical fittings, grids for locking the noise–absorbing panels and similar elements. Particular care was posed on modelling the bottom side rails (green) and cross members (orange), the corner fittings of the ground (clay), the shackle plates (yellow) and the welded connections (red) – see Fig. 4 (left side); 3D solid representation of these components was necessary.

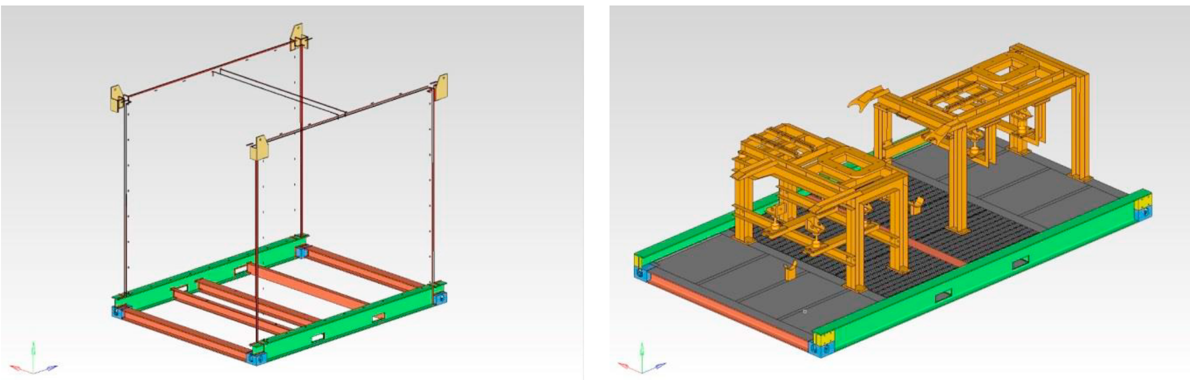


Fig. 4. Left: 3D components (similar for all the containers); Right: internal frames installed of central container.

With regard to the mesh element dimensions, an average value of 10 mm has been used for roof, sidewall endwall panels, while for the all other components a value of 5 mm was used. If not strictly necessary, *Quad* elements for 2D*, Hex* and *Penta* elements for 3D, were used. Containers consist of about 2˙700˙000, 4˙000˙000 and 4˙600˙000 nodes from the smaller to the largest respectively.

Two large chassis for the vibrating screens, for the hammer mills and for their engines are installed inside the central container (n.2); relevant loads and vibrations are expected on such components; they are also connected to the floor in such a way that they participate to floor stiffness. Main beams of such parts have been modelled privileging 2D elements (see orange components in Fig. 4).

Regarding materials steel density has been assumed 7.85*10^-9 ton/mm3, Young's Modulus (E) equal to 210000 MPa, and Poisson's Ratio equal to 0.3. The grade of the three steels used are: S235 JR, S275 JR, SCW480 having respectively the yield stress equal to: 235, 275 and 275 MPa.

3. Load cases on the structure

As indicated above, the container structures of the device do not reflect perfectly the typical architecture of shipping containers, but the operation conditions are quite similar. This is the reason why the structural behavior of the containers has been simulated according to the procedure and under specific boundary conditions described in the ISO 1496–1 reference standard that specifies the basic conditions and the testing requirements for ISO series 1 freight containers (ISO, 2013a, 2013b).

3.1. Mass loaded on the system

The masses of the internal elements have been provided by the manufacturer, so that most relevant ones are located on their exact position instead of being represented by distributed loads. Forces are applied as pressure on contact surface with floor, chassis or embossed metal sheets. Main elements installed in plants and their mass are listed in Table 1.

Table 1. Elements installed on the containers

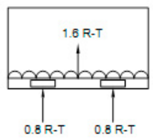
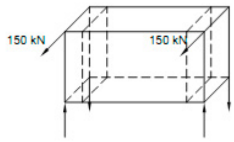
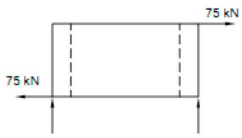
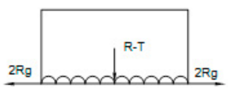
Location	Element	Mass (kg)
Container 1	Waste separator	86
Container 1	Vibrating screen	200
Container 1	Vacuum system and tubing	560
Container 1	Air compressor	220
Container 2	Mill Engine	1400
Container 2	Hammers mills	4000
Container 2	Vibrating screen	180
Container 2	Ribbon elevator 1	150
Container 2	Ribbon elevator 2	100
Container 3	Shearer machine	420
Container 3	Conveyor	120
Container 3	Table	50

3.2. Adaptation of existing technical standards

The loads provided by the ISO 668 and in the ISO 1496–1 are adapted (ISO, 2013a, 2013b). In particular, those load cases which are mainly aimed to analyze the interaction between containers – stacking up to 10 elements and transversal stiffness test (a stress usually related to stacking) – are particularly demanding, but are not representative of transportation and operating conditions of the structures here presented; therefore, some tests have been implemented using reduced load. In any case, restraint and lifting test have been considered since such cases are typical of plant transportation and installation. Other approaches are based on the direct measurement of stress under motion of the mechanical system (Cianetti et al., 2017), but are not applicable in this design phase due to lack of such information for the prototype. Certainly, further investigation on the plant should be carried out starting from data acquired on the prototype plant itself, including both data related to accelerations during transport and during plant operation, which includes machines generating shocks and vibrations such as shredders and vibrating screens.

Finally, the load cases considered for the analysis according to adapted ISO 1496–1 are shown in Table 2.

Table 2. Elements installed on the containers. Note: R is the mass loaded on the container; T is the tare masse of the container itself.

Load Case	Loads according to ISO 1496–1	Notes for application on the presented system
Stacking		942 kN load: removed
Lifting from top corner fitting		Loads applied on upper fittings
Lifting from forklift pockets		Loads applied on forklift pockets (existing in the model)
Rigidity – transverse		
Rigidity – longitudinal		
Restraint test		

4. Results

According to ISO 1496–1, upon completion of the test, *the structure shall show neither permanent deformation which will render it unsuitable for use nor abnormality which will render it unsuitable for use, and the dimensional requirements affecting handling, securing and interchange shall be satisfied*. Therefore, the main target of the analysis is to verify that stresses are within acceptable limits for the used materials and that displacements are within those limits which do not affect significantly the position and the stability of the frame and of the basements of the machinery used in the plant.

Table 3 summarizes the results of the test case selected and adapted as described in former paragraph. In general, all the test cases result in acceptable stress and displacements for the system, excluding the transverse rigidity one which is stressing the structures far beyond their capabilities. Particular attention has been paid to the deflection of the structure, and particularly on those parts installed on the floor, for which an acceptance threshold of 4 mm (maximum displacement) was assumed. Following paragraphs illustrates further details regarding the analyses. All pictures related to displacements use a 100X enhance factor for better visualization.

Table 3. Overview on test results

Test case	Overall stress on the structure	Local stress on fixing points/details	Overall displacement
Stacking	Acceptable	Acceptable	< 2mm max for container 2
Lifting from top corner fitting	Acceptable	Bolted/welded points to be improved	< 2.5mm max for container 2
Lifting from forklift pockets	Acceptable	Acceptable	≈ 3mm max for container 2
Rigidity – transverse	Unacceptable	Unacceptable	Unacceptable
Rigidity – longitudinal	Acceptable	Bolted/welded points to be improved	≈ 3mm max for container 3
Restraint test	Acceptable	Stackle plates to be improved	< 1.5 mm max for container 2

4.1. Stacking and lifting test results

According to Table 2, stacking and lifting case studies are all characterized by the fact that the loaded mass is only the one of machinery and containers. In all the cases, the stresses are within the acceptable limit of the steel used, even for lifting points. Also, maximum displacements are in all the cases in the range of 1–2mm, thus being acceptable. Considering the low average stress, however, the tests have been useful to identify local high stresses concentrated on certain points (e.g. bolts or welding), thus providing useful feedback to improve the design of such system details. See Fig. 5, Fig. 6 and Fig. 7 for the load cases (stacking, lifting from top corner fittings, lifting from forklift pockets respectively).

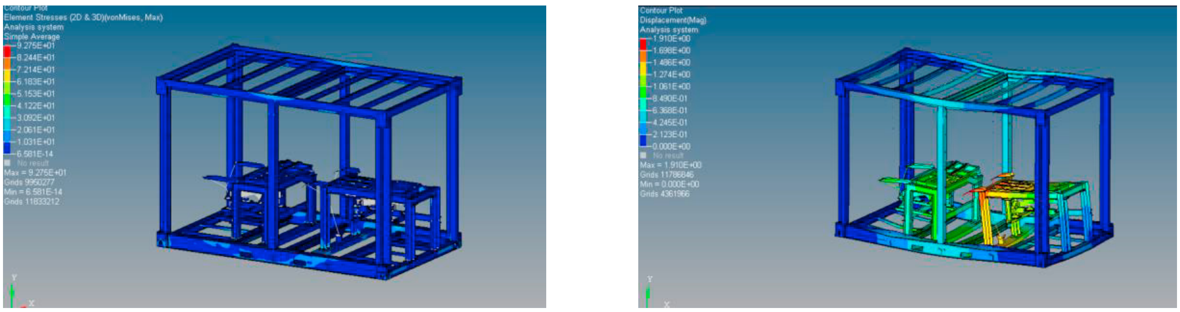


Fig. 5. Stacking test, results for container 2 (the most stressed of the three). Left: Stress is below 100 MPa for the main structure. Right: maximum displacement is within 2mm and is localized on machinery basement.

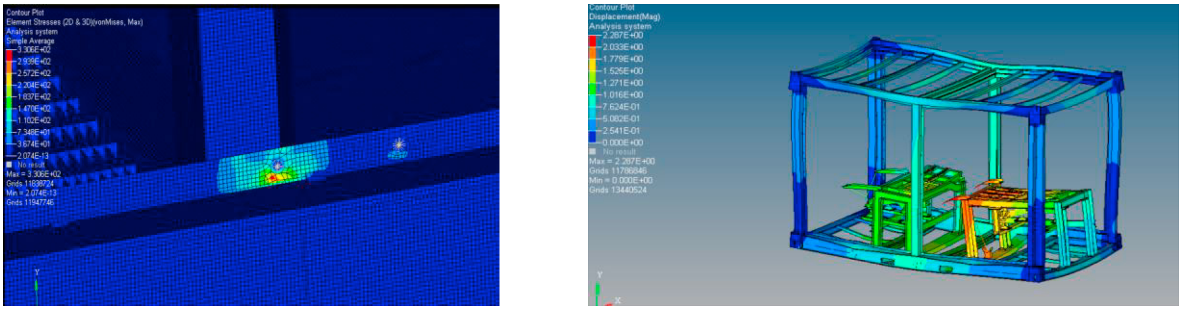


Fig. 6. Lifting from top corner fitting, results for container 2 (again, the most stressed of the three). Left: Stress is below 100 MPa for the main structure, but local stresses are higher. Right: maximum displacement is within 2mm and is localized on machinery basement.

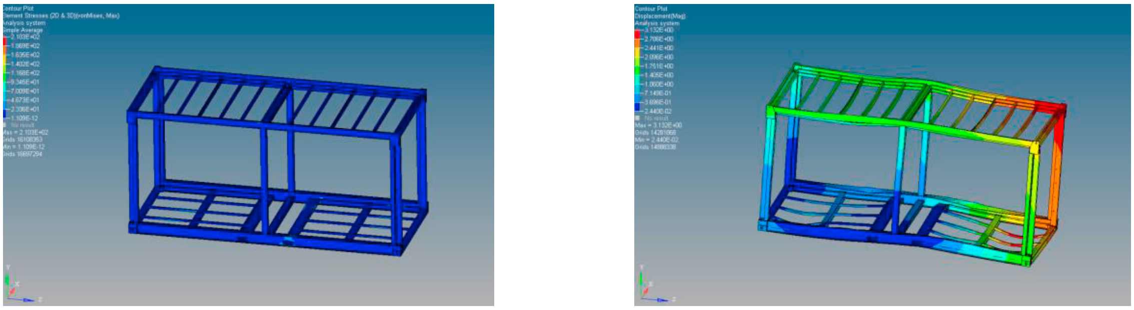


Fig. 7. Lifting from forklift pockets, results for container 3 (the most stressed of the three). Left: Stress is below 100 MPa for the main structure, but local stresses are higher – in any case, within acceptable limits. Right: maximum displacement is about 3mm and is localized on the most loaded side of the structure.

4.2. Rigidity and restraint tests

Rigidity and restraint test imply the application of forces to the system which are different from its typical load. The transverse rigidity test is demanding for the structure of the three containers and not only the stresses are beyond the admissible limits, but also unacceptable deflections (in the range of 15–25mm for the three structures) have been calculated. A brief examination of the results shows that the structures do not ensure sufficient stiffness because the elements of the roof are not designed to support transversal loads (see Fig. 8). However, since transversal forces are likely to appear in case of stacking with various other containers (e.g. in case of misalignments, movements during transport etc.), this adverse case study is not implying the need to redesign the structure, since stacking of multiple element is not expected. Longitudinal stiffness test, on the other side, provide acceptable results in terms of stress (again, excluding certain fitting points) on the structure; displacements are acceptable, resulting below 1mm, 1.5mm and 3 mm for container 1, 2 and 3 respectively. The shortest one (container 3) is, in any case, the most stressed due to the absence of an intermediate support on its side (Fig. 9).

Restraint test is particularly interesting since it shall be carried out to prove the ability of a container to withstand longitudinal external restraint under dynamic conditions, assuming a 2g acceleration value (e.g. in case of railway or truck transportation). The test is appropriate for the structures which are supposed to be transported without dismantling of their installed machinery, which represent a significant load. The test highlights that local stresses on restraint points are slightly above the yield value; this means that the material of such elements should be improved (see Fig. 10). Displacements – about 1 mm for container 2, as maximum value – are considered acceptable.

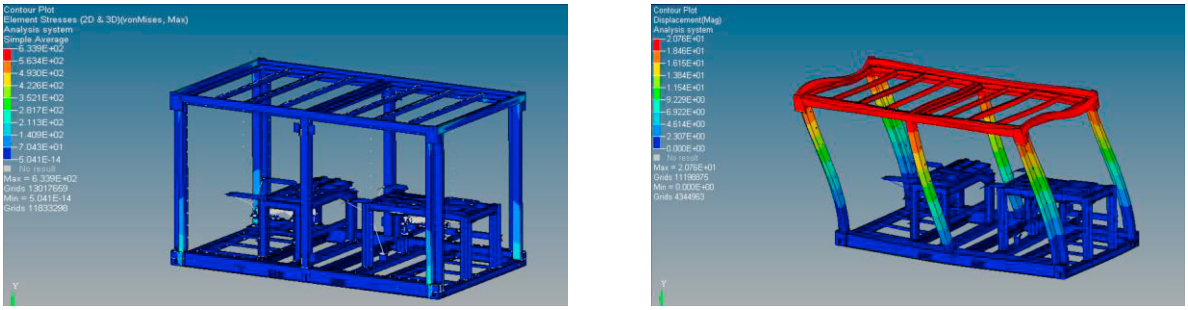


Fig. 8. Transverse rigidity test, results for container 2 (similar stress for all the containers). Left: Stress is above 600 MPa for the main structure, even if it is especially localized on certain linking points. Right: maximum displacement is beyond 20mm.

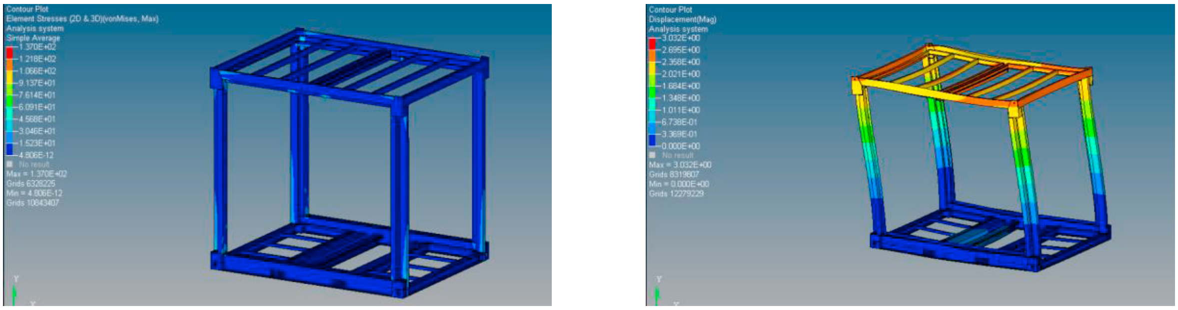


Fig. 9. Longitudinal rigidity test, results for container 3 (most stressed one). Left: Stress is below 140 MPa for the main structure, even if it is especially localized on certain linking points. Right: maximum displacement is about 3mm.

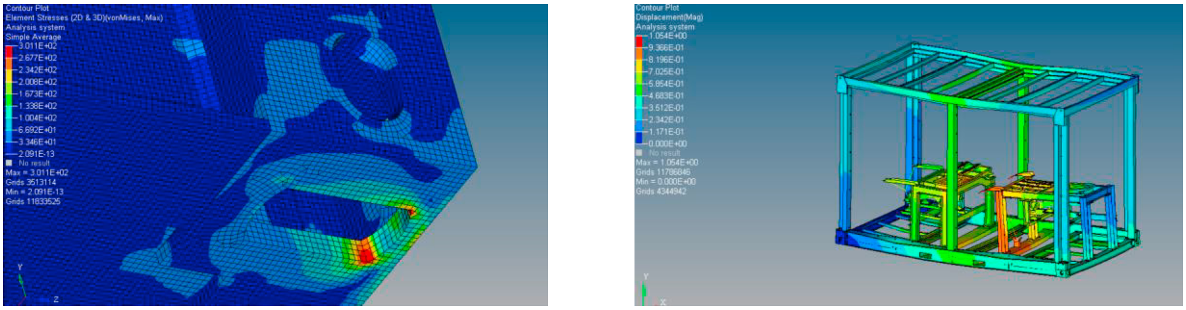


Fig. 10. Longitudinal restraint test, results for container 3 (most stressed one). Left: Stress is above 300 MPa for the main structure, even if it is especially localized on certain linking points. Right: maximum displacement is about 1mm.

5. Conclusions

The interest about plants for the treatment of WEEE is growing due to the increasing amount of flows expected in the future. Considering the large spreading of PV plants on territories, mobile systems provide the possibility to satisfy the need of ensuring proper treatment while reducing investments.

The objective of the study has been to analyze a group of three containers designed to be assembled constituting a unique plant, ensuring their stability and resistance for the peculiar use they are going to be subjected. For this reason, the test cases usually proposed for commercial freight containers have been selected and applied, thus proposing a methodology which is taking into account the need to handle plant parts during assembly/disassembly operations (e.g. lifting from various points has been examined), is appropriate for vehicle transportation (e.g. in case of longitudinal accelerations) and is potentially subjected to stacking. The proposal of such design standards is to enlarge the number of load cases and to propose demanding loads in comparison to those usually applied to static structures. Results shows that the structure under study is designed appropriately; only a few improvements on certain details are needed. The possibility to interact with other containers, however, is excluded due to the decision to use light structures for the roof and the upper parts (probably lighter than freight containers), while at floor level the system is appropriately design for the installation of heavy industrial machinery.

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https://ec.europa.eu/environment/eco–innovation/projects/en/projects/pv–morede

http://www.pvmorede.it/

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