CONTINUOUS MONITORING OF A STEEL STORAGE RACKING SYSTEM UNDER SERVICE CONDITION

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ABSTRACT

The paper presents the results of a continuous monitoring of a commercial steel rack, during a time interval of about 9 months under service conditions, in a logistic warehouse.. The purpose is to obtain a real time history of the dynamic stresses undergone by the rack, in field situation. The monitoring involved the whole rack, by mean of 32 accelerometers. Moreover a group of these data, containing the most important shakes, was analyzed to evaluate the damping factors that could be adopted for the design of this kind of structures. The research, performed in the frame of the UE program SEISRACKS 2 [1], is aimed to define new technical European design references for industrial racks, necessary for the large economic importance of storage warehouses, which should take into account also fatigue loading, and for the improvement of the design references for racks in seismic zones.

SOMMARIO

Nell’articolo si presentano i risultati di un’attività di monitoraggio continuo della durata di nove mesi su una scaffalatura industriale, sottoposta a carichi di servizio, in un capannone di immagazzinamento merci. Scopo del monitoraggio è la determinazione di una plausibile storia di carico dinamico agente su una scaffalatura in condizioni di servizio reali. Il monitoraggio ha riguardato l’intero scaffale, tramite l’applicazione di 32 accelerometri. Una parte rappresentativa dei dati, contenente le sollecitazioni più significative, è stata inoltre analizzata per valutare un possibile fattore di smorzamento da adottare nella progettazione di questo tipo di strutture. La ricerca, effettuata nel quadro del programma UE SEISRACKS2 [1] è finalizzata alla stesura di nuove norme tecniche di progetto europee per gli scaffali industriali, rese necessarie dalla grande importanza economica assunta dai capannoni di stoccaggio. Tale norma, inoltre, dovrà tener conto anche dei fenomeni di fatica indotti dai numerosissimi cicli di carico, oltre a costituire un adeguamento delle normative per le scaffalature in zona sismica.

1 INTRODUCTION

Racking systems, generally built up by the assembling of light cold formed steel uprights and beams, with hook-in connections among them, are widely adopted in storage warehouses. They can raise considerable height and, despite their lightness, are designed to carry tons of valuable goods, stored by means of pallets moved by forklift-trucks or by computerized automatic devices. Due to their peculiarity, these non-traditional structures require apposite design rules, especially in seismic zones, as the spillage of goods during an earthquake may represent a very large economic loss [2]. As an example, figure 1 shows the collapse of the Racking Systems in the warehouse of Ceramiche Sant'Agostino in Sant'Agostino (Ferrara) due to the recent 2012 Emilia earthquake [3] while figure 2 refers to the damages of Menu warehouse in Cavezzo (Modena). In this earthquake, many other storage warehouses were damaged. In some of them, the building collapsed and the rack survived (figure 2) while in some other cases the building survived and the rack system collapsed.

Fig. 1 and 2. Collapse of the warehouse and the racking systems of Ceramiche Sant'Agostino and of the Menu warehouse in Cavezzo, where racking systems survived

With recent technological improvement in Automatic Storage and Retrieval (AS&R) machines, the computerized storage of industrial products in racking systems is becoming more and more popular. As a consequence loading-unloading activities in these systems are very frequent, so there is a great and urgent need to introduce in Design Recommendation also the fatigue loading, presently missing at a European level in general. In this perspective, the results of a continuous monitoring activity on a real pallet rack in a storage warehouse carried out within the EU research project SEISRACK2 [3] are presented in this paper.

Except where adjacent to walls, storage racks normally are configured as two interconnected rows. Storage rack bays are typically *1.0-1.1 m* deep and *1.8-2.7 m* wide. The overall height of pallet rack structural frames, found in retail warehouse stores, varies between 5 and 6 meters. In industrial warehouse facilities, racking system can reach considerable heights, such as 12-15 meters or more (figure 2). Pallets typically have plan areas of approximately one square meter and a maximum loaded weight of approximately *10-15 kN*. The standard Europallet size is *800x1200 mm*. The rack industry calls the longitudinal direction the down-aisle direction, and the transverse direction the cross-aisle direction.

2 INSTRUMENTAL SETUP AND RECORDING

The constant monitoring was performed at a logistics center at the outskirts of Athens(Greece). The monitoring system consisted on 29 accelerometers installed on a steel pallet rack.

Additionally, a high resolution camera was installed to capture the number and location of pallets on the rack, as well as to identify the origin and location of the source of the vibration. The data presented hereafter refer to a period of about 9 months, during which the acquisition system was fully working.

A partial monitoring system was installed also during a previous research project (SEISRACKS1 [4]). The indication obtained suggested the importance of a complete monitoring system during an adequate time interval, which was adopted in the following project SEISRACKS2 [1].

In total three bays of a pallet rack system were monitored, (*2.7 m* each bay, for three pallets places per bay), with a depth of *1.1 m* and a height of *6 m*. The rack is on a single row, not coupled to another rack. It has one end free, situated at the crossing of two corridors.

Figure 3 shows the position of the 29 accelerometers installed on the rack. Additionally a three dimensional accelerometer was placed on the ground. Apart this one, no sensor was set to register vertical accelerations. The three dimensional accelerometer on the ground and all six accelerometers at the top of the rack acted as triggers for recording (at *0.015g* for the ground, and *0.025g* at the top) but the base accelerometer didn't worked properly. A general conclusion that can be derived from the recordings is that maximum accelerations, both in cross aisle and in down aisle direction, can be recorded in every position of the rack system, not particularly at the top, as expected in case of ground motion. Even though this monitoring system was on site since the previous project SEISRACKS1, it was not working properly. Actually, the system was subjected to a few episodes of "sabotage" (the camera was intentionally covered with boxes, to prevent pictures to be taken, the acquisition unit was damaged a couple of times and, despite the presence of a protection cabinet, totally destroyed when water was intentionally poured on it). This was most probably due to the "discomfort" of the workmen feeling themselves controlled during their working activity. The time interval considered in this paper, apart from two blank weeks due to a malfunction in February, is from November, 22 2012 to August, 9 2013 - 261 days (248 days of recording). The recorded files report each one 32 columns; each column corresponding to a sensor. The sampling rate was *200 Hz* (*0.005* seconds).

3 DATA ANALYSIS

Table 1. Event classification

Month	**Registered Files**	**Significant Files**	**Events**	**Small events**	**Events with max acc. >0.10g**
November 2012 (9 days)	36	30	40	5	13
December 2012	98	86	140	31	59
January 2013	134	96	167	27	66
February 2013	2255	148	154	36	51
March 2013	3792	275	275	63	88
April 2013	1967	373	373	72	98
May 2013	2397	389	389	69	126
June 2013	2705	424	424	99	119
July 2013	2105	180	180	43	46
August 2013 (9 days)	580	27	27	3	10
Total	**16069**	**2028**	**2169**	**448**	**676**

A very large amount of data was recorded. For 248 days we had 16069 files. It's not possible to consider the average number of shakes by day, because this depends mainly on the loading and unloading activity on the racks and, in what regards shake intensities, on the weights moved. As reported in table 1, the maximum activity registered in March 2013 (3792 files) gives an average value of 120 shakes per day, in comparison to an average of a few records (3 – 4) per day in November and December 2012. In order to distinguish significant shocks from small tremors, only the files containing at least one sensor with an acceleration value ≥*0.05g* were considered. Despite the conservative low value of the acceleration considered, the number of files taken into account reduced to 2028. Moreover not all the sensors worked properly, so they had to be disregarded. The available recording positions are only 19 (see figure 3). It's feeling of the authors that these sensors, which were the most accessible ones to the workmen, were intentionally damaged. For this reason, it was considered useless to try to replace the instrumentation, and it was chosen to maintain the system in the initial condition.

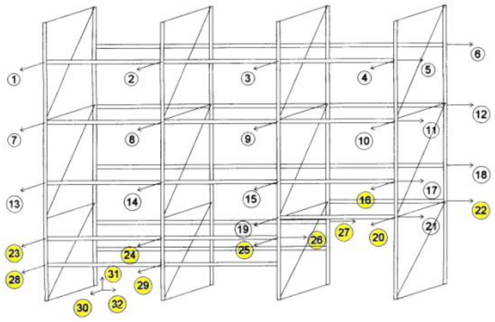


Fig. 3. Sensor position and disregarded (no record ≥*0.05g*) or bad running sensors

4 SHAKING EVENTS AND PRELIMINARY DATA ANALYSIS

As the duration of recording is quite long, 60 seconds after the triggering, it was decided to define single significant shocks contained in a file as shaking-events as following: an event is a group of data recorded after an acceleration value ≥*0.05g*, whose last value ≥*0.05g* is separated from the next one in the whole file, considering all sensors, by a time span of at least 4 seconds. That is, two values ≥*0.05g* belong to two different shocks if they are separated for at least 4 seconds by only small tremors in the whole rack.

Table 1 shows the results of this preliminary analysis of the data. With respect to the 2028 significant files, the shocks registered are 2169; moreover among the events considered, 448 can be set as small events, as they have only one *0.05g* value of the acceleration, therefore disregarding them the number of significant shakes reduces to 1721. On the other hand, there are 676 events with accelerations larger than *0.10g*. Among these, 186 shakes have a peak acceleration larger than *0.30g* and in 55 of them the acceleration is larger than *0.50g*. It can be seen that in the months with the largest amount of shocks, the average trial is from 10 to 15 events every day. A preliminary overview of the data showed that the shakes are generally quite short, of the order of a fraction of second or about one second. Anyway there are some exceptions, as 260 shakes are longer, up to a few seconds (time interval between two acceleration values ≥*0.05g*).

The selected files were analyzed in order to identify the most stressed positions on the rack. This analysis was performed classifying the sensors according to three descriptive criteria:

- Sensors that registered more than 2000 values of acceleration ≥*0.05g*
- Sensors with more than 30 values of acceleration >*0.30 g*
- Sensors with registered accelerations values >*0.5 g*

It can be noticed that the sensors with more than 2000 values of acceleration ≥*0.05g* are all those in correspondence of the external upright (sensor 4 at the top, in cross-aisle direction, and all

those in down-aisle direction: sensors 5, 11, 17, 18 and 21). This is probably due to a wrapping machine close to this column, at the base of the rack. This fact was not considered a fault for the analysis of the data, because the aim of the study was the monitoring of a real situation.
Almost all the active sensors (16 out of 19) registered more than 1000 acceleration values ≥*0.05g*.

Table 2. Larger events

Month	**events with acc. >0.30g**	**events with acc. >0.30g excluding sensor 21**	**events with acc. >0.50g**	**events with acc. > 0.50g excluding sensor 21**
November 2012(9 days)	4	4	1	1
December 2012	14	6	3	1
January 2013	6	4	2	1
February 2013	11	6	5	5
March 2013	19	14	10	7
April 2013	24	17	10	6
May 2013	23	19	8	8
June 2013	23	16	10	3
July 2013	6	3	3	2
August 2013 (9 days)	7	2	3	1
Total	**186**	**91**	**55**	**35**

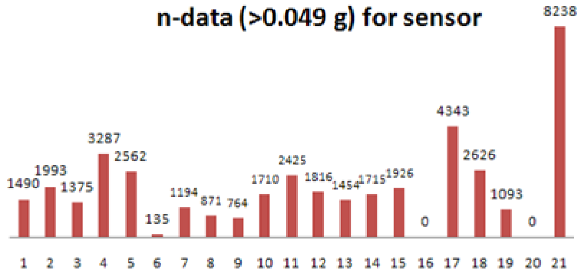


Fig. 4. Number of significant values per sensor

Figure 4 indicates the number of values ≥*0.05g* registered by every sensor. In figure 5 is reported the number of values of acceleration larger than *0.30 g*, while figure 6 highlights the sensors with more than 30 values of acceleration larger than *0.30 g*. They are almost all in cross-aisle direction, at mid-height of the rack, while the corner upright on the right shows for the sensors 17 and 21 an acceleration in down-aisle direction. It must be noticed that the corresponding cross-aisle sensors of the upright, number 16 and 20, were not working properly (see figure 3). The large amount of 252 values for sensor 21, corresponding to 95 shakes, 20 of them with acc. *>0.50g*, is probably due to the corner position of the upright at an aisle crossing that is more prone to shocks by the fork elevators. The number of important shakes with peak acceleration *>0.30g*, excluding the lower corner sensor 21, are only 91; they occur from 1 to 3 times per week (see table 2).
Almost all active sensors registered at least an acceleration value larger than *0.50 g*, *a* s it can be seen from figure 6, that indicates the maximum values of acceleration registered by every sensor. It can be seen that also high values of acceleration, about *1.0 g*, are possible.

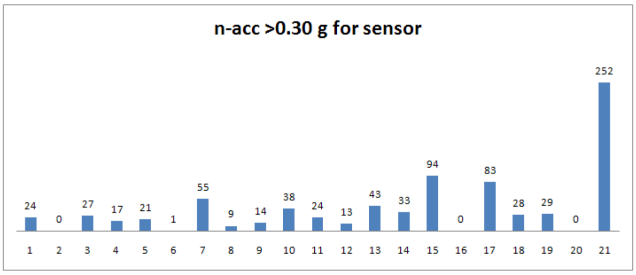


Fig. 5. Number of acceleration values > *0.30g* for each sensor

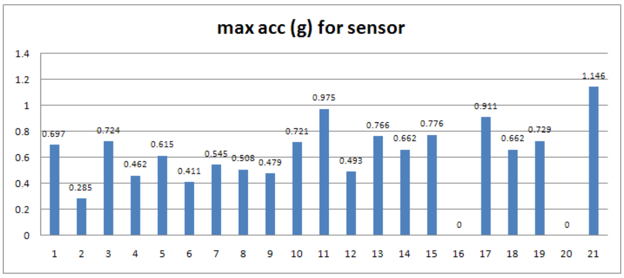
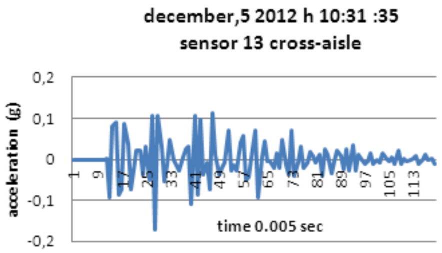


Fig. 6. Maximum acceleration recorded by each sensor

5 MOST STRESSED PARTS OF THE RACK

Considering the last two criteria applied to each sensor, the most stressed points are in correspondence of sensors 7, 10, 13, 15 in cross-aisle direction, and 17 and 21 on the corner upright in down-aisle direction. Only these two sensors satisfy all three criteria: they underwent maximum accelerations larger than *0.50g* and more than 30 values of accelerations >*0.30g*, moreover they registered also more than 2000 values of acceleration ≥*0.05g*. A typical record for sensor 13, similar to those of the other sensors, is shown in figure 7, for the shock of December, 5 2012 h 10:31:35, the largest one undergone by the rack. During it the maximum acceleration of *1.146g* was registered by sensor 21 (see figure 8). The shake duration is about 0.4 seconds, with a maximum acceleration of *0.17g*. In sensor15, which is nearer to sensor 21, the peak acceleration was *0.47g* (see figure 9). The frequencies of the rack indicated by the data, as can be seen in the figure, are quite high, about *50-60 Hz*. A more precise value of the frequencies cannot be indicated, because it depends on the load situation of the rack. Nevertheless, considering also many other recordings, these values can be assumed as representative of the behavior of the rack.

Sensors 11, 17 and 21 recorded acceleration values larger than *0.9g*. They are all in down-aisle direction in the corner upright. For sensor 21, which is in the lower position, there are also values larger than *1.0g*. This can be explained assuming that these large accelerations are due to bumps on the upright of the fork lift trucks operating in the warehouse. The performance of sensor 21 shows 9 values of acceleration in the interval *0.90-1.00g*. Moreover, 2 other values >*1.00g* are in the shock happened on December, 5 2012 h 10:31:35, reported in figure 8. There are two close strong impulses, at about 0.1 seconds of distance.



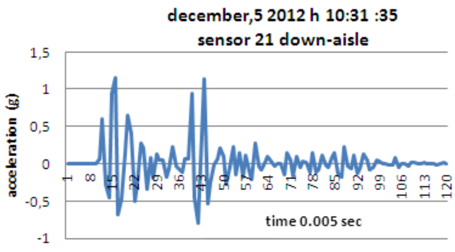


Fig. 7. Typical shake recorded by sensor 13 **Fig. 8.** Sensor 21 - shock of December, 5 2012

6 DAMPING

Damping in a rack depends on many factors, some constant, as the type of connections in the rack, and others changing in time, as the loads on the racks and their distribution, which affect the friction forces in the connections. In order to obtain an indicative damping behavior of the rack in real service conditions, a group of events with large peak accelerations have been analyzed.

Table 3. Sensor 15 – Damping for record on December, 11 2012 h 13:28:15

	Positive			Negative		
Peak interval	1T	2T	3T	1T	2T	3T
Acceleration	0,362	0,362	0,362	0,448	0,448	0,448
interval	0,303	0,169	0,073	0,166	0,072	-
Damping %	2,83	6,06	8,49	15,81	14,55	-
Average Damping %			5,79			15,18

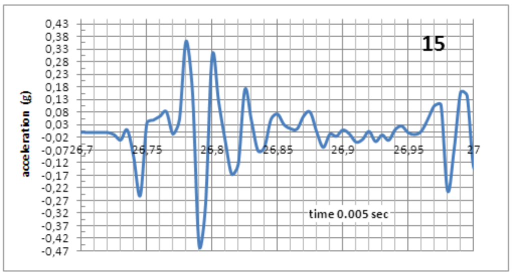


Fig. 9. Sensor 15 – Peak acceleration on December, 11 2012 h 13:28:15.

Damping was evaluated considering the decrease of the acceleration from the peak value, both in positive and negative direction, taking into account the first three or four subsequent peak values, and determining the average of these results. Many times it's difficult to evaluate damping, as only one or two significant peaks of acceleration are available. An example for sensor 15, file 11_12_201213_28_15 (date and time of the event) can be seen in figure 9 and Table 3.

Considering a group of 17 shocks with large values of peak acceleration, recorded on the corner-upright by sensor 21 and sensor 17, positioned immediately over sensor 21, both down-aisle, we have for sensor 21 an average damping of 9.1%, with a lower value of 4.3% and for sensor 17 an average damping value 6.5 %, with a lower value 3.5%. So, as a general indication, a global 6% damping factor in down aisle direction seems acceptable to describe the dynamic behavior of the rack. In Table 4 are reported the damping values derived by 4 recordings with maximum peak acceleration in sensor 4, cross-aisle, on the top of the corner upright. The average value yield by these data is 7.4%. Therefore, as an indication on the expected damping, a value of 6% seems enough conservative, considering also that the position of the corner upright is the less restrained one.

Table 4. Max acc. in sensor 4 - Damping in sensor 4

Date-event	Max acc. *(g)*	Sensor 4 Average Damping %	
		positive	negative
3_1_201312_26_39	0,113	8,7	5,6
3_1_201315_16_39	0,111	9,0	5,6
15_1_201313_3_26	0,106	5,7	3,6
18_1_201312_51_46	0,08	8,3	12,4

7 CONCLUSIONS

The performed monitoring allowed a description of the dynamic loading undergone by a rack in a real industrial situation. Considering significant shocks in the different parts of the rack only those with acceleration $\geq 0.05g$, 10-15 shocks per day are undergone by the rack during the periods of full activity. Apart from the corner up-right, from one to three important shakes per week, as a global average, with acceleration $>0.30g$ occurred and were recorded. The monitoring, showed that also large shocks are possible, with accelerations $>0.5g$ in all parts of the racks, and in some cases the acceleration can be near to or larger than $1.0g$. The shakes had generally an impulsive shape, with a rapid decrease of the acceleration, and lasted generally less than one second. The typical frequencies of the shakes, were from 50 to 60 Hz. An analysis of some important shocks, undergone by the structure suggested an indicative global 6% damping factor.

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KEYWORDS

Continuous monitoring, Cold formed steel members, Racking system, Acceleration, Damping factor.