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PAINTINGS

Packing systems for paintings: Damping capacity in relation to transport-induced shock and vibration

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ABSTRACT

The demands on current packing systems for the transport of paintings on textile supports are manifold. These must protect against various types of external impacts such as climate and mechanical stress, as well as transport-induced shock and vibration. A selection of packing systems and materials was tested in field and lab sequences with respect to their damping effects within the context of a research project on the transport of fragile

INTRODUCTION

The new results on the damping capacities of selected packing systems for paintings build on the findings on the damping capacity of backing boards and glazing on paintings presented in 2011 (Bäschlin et al. 2011), whereby some of the back protection systems tested within this former study produced very effective damping, whereas others had little protective effect or induced negative resonance effects.

Once the applied research concept was defined, the next step consisted of testing the packing systems commonly used by art transport companies. A selection of packing systems and materials was tested in field and lab sequences with respect to their damping effects by running comparative experiments with the art transport partners. These packing systems, developed by the art transport companies, combine the companies' own empirical knowledge with customers' experience (e.g. conservators) and economic considerations. Several types of polyethylene foams (Ethafoam), flexible polyurethane foams, polyurethane composite foams and polystyrene (Styrofoam) are commonly used protective materials (for vibration, shock and thermal insulation). Packing systems containing damping foam materials have been systematically discussed by Marcon (1991b), who has developed the PadCAD software (Marcon and Strang 1999) to simplify the design of protective cushioning systems.

The comparative experiments run with similar foam materials allow the conclusion that many of the systems applied successfully dampen severe shocks. Continuous vibrations, however, are often enhanced rather than eliminated. Experiments run to study the vibration damping behaviour of the various foams deliver relevant information and some explanations: all foams exhibit pronounced resonance behaviour close to the natural frequency range of paintings of 4–50 Hz[1] almost regardless of the static load (load per unit area of cushion material). Some of the applied foams are thus of limited use as a protection against vibrations for paintings on textile supports. Furthermore, the quantitative results show that not all of the vibration enhancements identified can be related to the material behaviour. Explanations may be found in the complexity of material and geometric interactions of custom-made protective boxes. In this context, the influence of geometric deficiencies has been underestimated so far.

paintings. The systematic quantification of various materials and combinations thereof delivered a direct comparison of the systems and uncovered an unexpected need for action with respect to the damping capacity of vibration immissions. Field tests of commonly used packing systems revealed resonance behaviour leading to the amplification of vibrations on test paintings. The results of field and laboratory experiments clearly show that vibration damping with the usual damping materials is difficult to achieve. Low controllability of the performance in the workflow aggravates the situation. This may change the predicted vibration behaviour. The movement of the sidewall of the truck may induce increased vibration.

The new findings of the comparative experiments run with the art transport partners revealed a considerable need for development. The study of the behaviour of fragile artwork under continuous vibration conducted during the ongoing research project[2] revealed a critical level of tolerable strains (induced by the vibration levels) that is much lower than quoted in the literature (Michalski 1991, Lasyk et al. 2008). The project is a joint approach combining conservation scientists (Bern University of the Arts – BUA), engineers (Bern University of Applied Sciences – BUAS), an art insurance firm and several art transport companies, as well as fine art museums (www.gemaeldetransport.ch).

MATERIALS AND METHODS

For the field experiments, a number of identical test paintings with frames were produced. Data loggers with triaxial acceleration sensors were mounted on each bottom stretcher bar. The selection of packing materials was based on the systems commonly applied by art transport companies. Seven different packing systems were explored, totalling 17 individual packing items. The focus of this paper is the comparison between four different insulated boxes, a simple cardboard box and, a so-called "art case" or flight case. The insulated boxes are specifically designed for the damping of fragile artwork on long-distance transportation. For short transfers, cardboard boxes, or "art cases", are often used. The systems are presented in Figure 1 and described in Table 1.

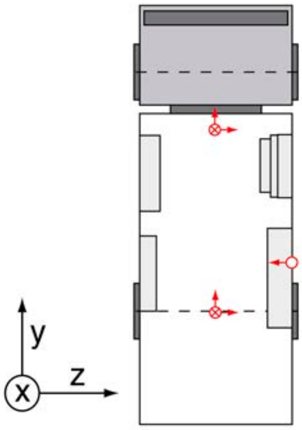
Figure 1
Packing systems tested: (1) cardboard box, (2)–(5) insulated boxes, (6) flight case. Descriptions are listed in Table 1

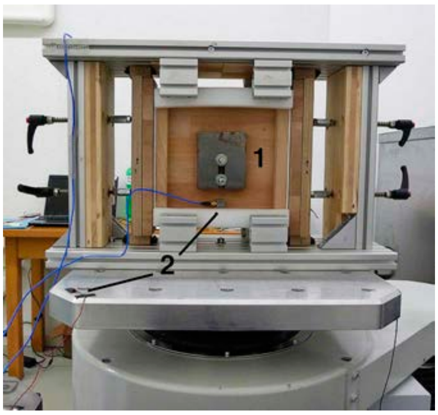
Table 1
The six discussed packing systems and their internal build-up (see also Figure 1)

packaging	materials (from inside to outside)	weight (kg)	transport
(1) carboard box	Tyvek, plastic foil, Ethafoam, cardboard	9	A
(2) insulated box	pergamin, plastic foil, polyurethane composite foam corner, cardboard, polystyrene, plywood	68	A
(3) insulated box	traveling frame with fitting, Ethafoam corner, cardboard, polystyrene, plywood	105	A
(4) insulated box	Tyvek, plastic foil, Ethafoam, polystyrene, plywood	56	B
(5) insulated box	pergamin, plastic foil, Ethafoam, cardboard bottom, polyurethane foam, Ethafoam sides, polystyrene, plywood	52	C
(6) flightcase	pergamin, bubble wrap, polyurethane foam bottom, cardboard dividers, polyurethane composite foam and blankets as fillers	-	C

The experiments were conducted in three air-sprung and temperature-controlled trucks, with a similar capacity of 14–18 metric tons. The truck movements were logged at three spots on the loading platform (triaxial) and the sidewall (uniaxial) (Figure 2). The transport cases were fixed routinely to the sidewall by the art transport personnel. Different routes were chosen to represent the various travel modes (city traffic, highway, freeway). In addition to those standard situations, some extreme 'events' were also logged, such as an emergency stop and a short drive through a quarry. Each transport sequence was about one hour in duration. The comparison of acceleration values between vehicle and test painting delivered quantitative data on the damping capacity of the different packing systems. The movements were recorded with a data rate of 1600 Hz. The main statistical parameters were the maximum and average (root mean square) acceleration, as well as the power spectral density (PSD).

Parallel to the field tests, laboratory sequences were run on single packing components. The load-dependent vibration absorption, as well as the shock-absorbing behaviour of the different foams and damping materials, was quantified. A special rack was designed for the shaker to replicate the geometrical situation in a transport box (Figure 3). The damping materials were stressed with a test volume of adjustable mass. The frequency response was measured by the ASTM D 4728 (truck) standard immission. The shock test consisted of trapezoidal shock loads at five strengths.[3] All experiments were run in five replicates and evaluated statistically. The frequency behaviour of individual materials and selected combinations thereof is presented in amplification-attenuation plots, whereas the shock behaviour is plotted in so-called cushion curves.





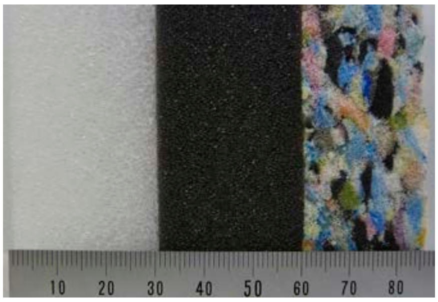


Figure 2
Principal directions and positioning of the sensors on the loading area as well as the sidewall of the trucks

Figure 3
Rack on the shaker to analyse the dynamic properties of the cushioning materials. The mass (1) is adjustable. Acceleration sensors (2) measure on the mass and on the table surface

Figure 4
Materials tested (from left to right): polyethylene foam (Ethafoam), polyurethane foam and polyurethane composite foam

EXPERIMENTAL RESULTS

Although fairly high acceleration values were documented during field tests, the average (rms) largely corresponded to the measurements in real shipments (Palmbach et al. 2012). Extreme events caused accelerations of up to 70 m/s^2 on the vehicle perpendicular to the road (x-direction). Freeway sequences achieved a maximum of 24 m/s^2. The highest average (rms) documented was 2.7 m/s^2. Standard freeway sequences typically average between 0.9 and 1.8 m/s^2 (Table 2). Although the three trucks used were different models and generations, they showed similar power density spectra (Figures 6–7). In all spectra, typical resonances of the suspension (at 5 Hz), tires (15–25 Hz) and engine/drivetrain (60–80 Hz) are clearly visible (Marcon 1991a). The analysis of the sensor positioning showed that acceleration on the sidewalls is much higher than at the level of the loading platform. According to the size of the surface, the mean acceleration was 1.7–3.4 m/s^2 (rms). The difference between the front and rear measuring point is less significant. Extreme events mostly caused a high maximum above the rear axle (Table 2). The discussion is focused on the two most relevant acceleration directions. Maximum values were recorded perpendicular to the street surface (x-direction), while immissions perpendicular to the painting surface (z-direction) are considered most harmful to the painting.

Table 2
Maximum and mean values of the immissions recorded on each of the three different transport sequences. All three sensor positions (front, rear axle and sidewall) are displayed.
* Values are associated with extreme events: A = drive through a quarry; C = speed bump

transport	x-direction (front/axle)		y-direction (front/axle)		z-direction (front/axle)		z-direction (wall)	
	max. (m/s^2)	rms (m/s^2)	max. (m/s^2)	rms (m/s^2)	max. (m/s^2)	rms (m/s^2)	max. (m/s^2)	rms (m/s^2)
A	13.0 / 70.1*	1.0 / 1.8	7.1 / 21.0	0.6 / 0.6	9.1 / 31.4	0.7 / 0.6	23.1	1.7
B	13.7 / 13.9	1.3 / 0.9	11.1 / 6.8	0.8 / 0.5	14.3 / 5.6	1.0 / 0.5	23.6	3.1
C	16.7 / 38.7*	1.0 / 1.1	4.8 / 11.8	0.3 / 0.4	6.1 / 5.5	0.5 / 0.4	44.3	3.4

Table 3 shows the statistical values of the packing systems discussed. What stands out is that both maximum and mean values for most systems are identical to the values measured on the truck. Thus, none of the packing systems manages to successfully reduce vibrational stress on the objects. Different positioning within the truck had no significant effect on the x-direction of the painting's vibration. Furthermore, vibrations perpendicular to the sidewall (z-direction) are almost fully translated to the packing (and contents), especially near the centre of the wall (highest displacement).

Table 3
Maximum and mean values of the measured movements of the test paintings in the different packing

packaging		x-direction		z-direction	
	transport	max. (m/s²)	rms (m/s²)	max. (m/s²)	rms (m/s²)
(1) carboard box	A	9.3	0.86	8.6	1.00
(2) insulated box	A	15.8	2.24	12.8	1.11
(3) insulated box	A	26.1	1.15	18.8	1.56
(4) insulated box	B	15.6	1.35	16.2	0.88
(5) insulated box	C	31.3	0.76	13.6	1.21
(6) flightcase	C	21.1	0.85	16.5	0.88

The laboratory tests were intended as a first approximation to an explanation of the system's performance. Each of the selected damping materials recorded distinct characteristics. For the packing systems under discussion, only a limited set of damping materials was of relevance. These were Ethafoam, polyurethane foam and polyurethane composite foam (Figure 4).[4] Plywood, cardboard and polystyrene were less relevant because they are largely inelastic in the specific load and frequency range.

Figure 5 shows the results of the vibration and shock test. Ethafoam is a relatively hard material. The resonance frequency is thus high at low static load. Shock loads of up to 100 m/s^2 may be attenuated even better at weights over 1500 kg/m^2. Ethafoam changes its properties only slightly over a wide load range. Polyurethane composite foam is also resilient over a large load range. It has good damping capacity under shock loading. Polyurethane foam (30 mm), on the other hand, works best at much lower loads of around 400 kg/m^2. It behaves ideally in a very restricted load range

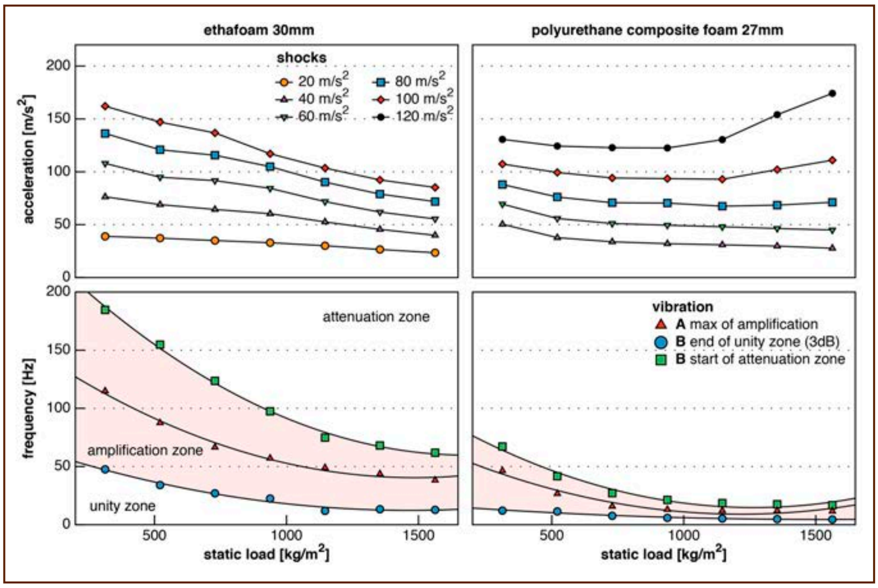


Figure 5
Dynamic properties of Ethafoam and polyurethane composite foam. Shock tests are displayed with cushion curves (top); resonance behaviour is shown in the amplification-attenuation plot (bottom)

(Figure 6). Above 500 kg/m², the polyurethane foam becomes overloaded. The dynamic properties are modified by the combination of materials. One of the tested combinations was Ethafoam and polyurethane foam. While the load is on the Ethafoam, the static load on the polyurethane foam outside is halved because of an increased load area. This explains the higher load-bearing capacity of the combination, despite the lower layer thickness of the polyurethane foam.

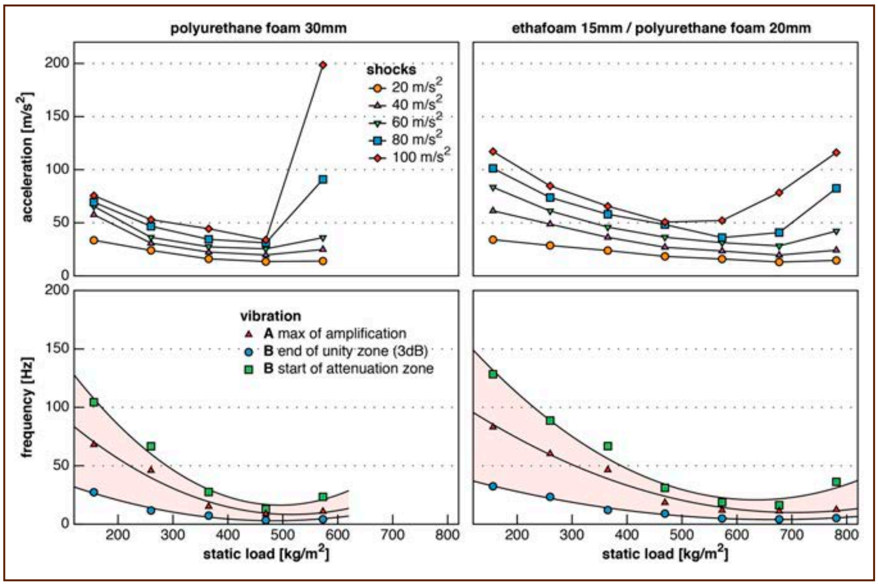


Figure 6
Dynamic properties of polyurethane foam and a combination of Ethafoam and polyurethane foam. Shock tests are displayed with cushion curves (top); resonance behaviour is shown in the amplification-attenuation plot (bottom)

In practice, determination and calculation of the ideal static loading of damping materials has proven to be quite difficult. In most systems multiple layers of damping materials are involved. It has been observed that the static load often becomes very small. For example, if the entire bottom edge of the frame is cushioned (i.e. (1) cardboard box), the static load on the Ethafoam is theoretically about 90 kg/m². All tested foams are below the attenuation threshold at this load. At best, vibrations are translated without attenuation, or, at worst, they are amplified.

The behaviour of the cardboard box (1) is virtually neutral when perpendicular to the road surface (x-direction) (Figure 7). In the range from 40–70 Hz, where the immission is greatest due to resonances of the engine and drivetrain, effective damping was recorded. In the case of the insulated box (2), however, amplification was documented over the entire range from 10–20 Hz and 40–100 Hz. Perpendicular to the image plane (z-direction), the differences are less pronounced. Amplification in system 2 (insulated box) can be explained by the material properties: for the given static load of about 200 kg/m², the frequency range recorded (15–75 Hz) lies almost entirely within the amplification zone. The damping of system 1 (cardboard box), however, cannot obviously be related to material properties. According to the analysed properties of Ethafoam, it does not attenuate frequencies at 60 Hz below a static load of 1600 kg/m².

Even apparently similar systems behave distinctly differently. An example gives a comparison between insulated boxes (3) and (4). Both boxes were fixed in the same central position of the truck's loading area. Box (4) consisted of simple layers of thermal insulation and protective material around the object, whereas the test painting in box (3) was mechanically fixed to a transporting frame. The frame in turn was held by a system of fitted damping and insulation materials within the wooden box. In x-direction, the simpler system (4) behaved neutrally with only slight amplifications between 10–20 Hz (Figure 7). System (3) with the cushioned transport frame, on the other hand, recorded amplifications in the low frequency range along z on the test painting. The fact that the 9 Hz peak is visible even in the x-direction implies that the test painting was moving within the box. The fittings used have a riveted joint with some tolerance, which might have been the origin of the amplification in the range of 30–55 Hz (z-direction) and 20–40 Hz (x-direction).

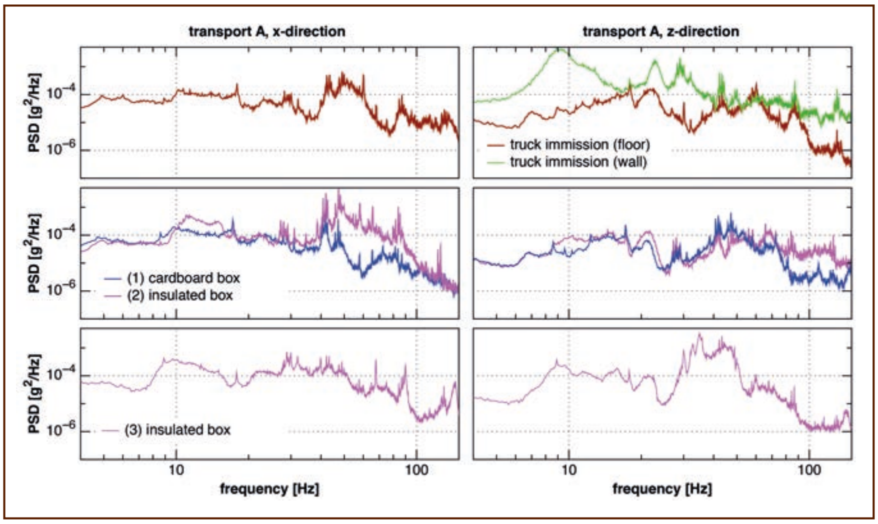


Figure 7
Power spectral density (PSD) plots of transport A. Truck spectra (top) may be considered as an input. Compared to packing plots (1)–(3), spectral attenuation/amplification can be observed

Another source of amplification was located at the interface between vehicle and packing: the wheels of the flight case (6) – attached for easy handling – seemed to act as springs in the z-direction, amplifying immissions in the range from 15–50 Hz. Concurrently, there was some attenuation along the x-direction above 20 Hz (Figure 8). The insulated box (5), on the contrary, exhibited near neutral behaviour: the test painting was padded with polyurethane foam in the z-direction, which is suspected to be the origin of the recorded amplifications.

DISCUSSION

Previous research on the shock impact and vibration induced by the air-sprung truck delivered mainly acceleration maxima along the x-direction, describing shock impact during truck transportation (Saunders 1998). Experimental results of the ongoing project, however, revealed that the assessment of the vibration (x and z), the consideration of the z-direction, and an assessment of the average value (rms) are even more relevant. Furthermore, the power spectral density (PSD) (Figures 7–8) characterising the dominant frequency range of the truck-induced vibration is of great relevance.

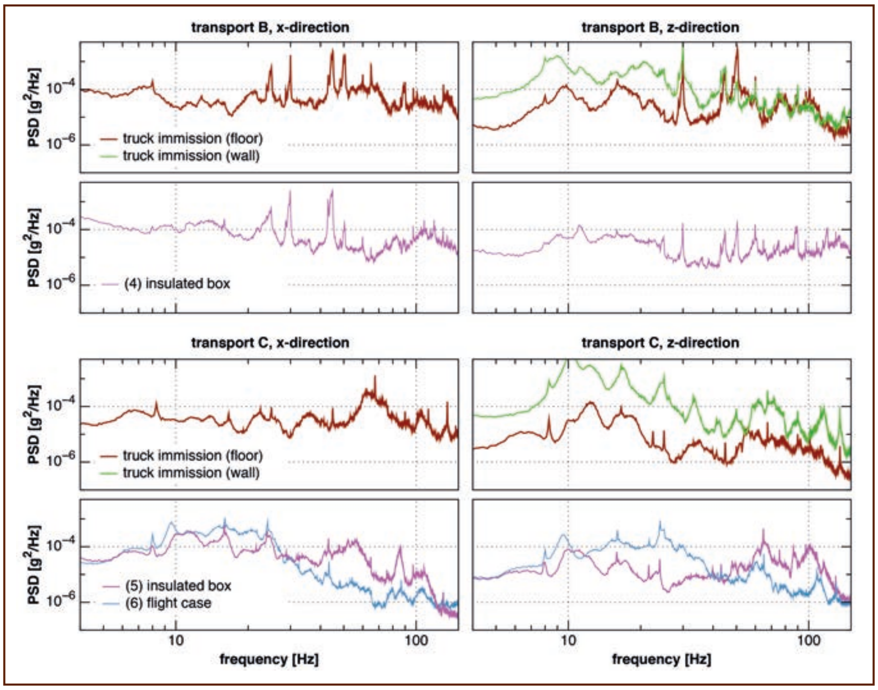


Figure 8
Power spectral density (PSD) plots of transport B and C. Truck spectra (top) may be considered as input. Compared to packing plots (4)–(6), spectral attenuation/amplification can be observed

The basic concept of shock and vibration damping implies that the static load of cushioning materials is increased to a point where critical frequencies are located in the attenuation zone, while shocks of a specified strength must be sufficiently absorbed. Ideal static loads mentioned in the literature and confirmed by the laboratory experiments are difficult to achieve in practice, as noted by Green (1991). Within the commonly applied load range, the materials fail to effectively dampen vibrations within the relevant frequency range up to 100 Hz. Although no amplification would be expected in the unity zone, these foams exhibit pronounced resonance behaviour in the relevant frequency range. The best results recorded in the field experiments were achieved by systems set out to increase foam hardness with small static loads. Systems based on increased static loading or the use of soft foams eventually failed, leading to amplifications in the range of 5–100 Hz.

The build-up of packing systems leads to a complex interaction of geometric and mechanical factors, superimposed on the mechanical behaviour of the damping materials. Practical implementation further adds to the complexity, i.e. the fitting of the cushioning materials needs to be precise. If form and force closure are not given, either ullage or compression occurs in one spatial direction. This may change the predicted vibration behaviour. Mobility normally leads to increased values, whereas compression leads to a resonance shift. Accessory parts of the packing structure with mechanical tolerances (i.e. fittings or wheels) may enhance the vibration and be the source of additional resonances. At the interface between truck and packing, there is the potential of an increased portion of vibration translated from the sidewalls to the packing in certain configurations. The observed vibration enhancements due to resonance are at a level where damage to fragile objects cannot be excluded. The natural frequency of a painting is dependent on numerous factors: size, material and tension. Additionally, it is influenced by the combined system of backing board and glazing (Bäschlin et al. 2011). The system exhibits multiple Eigen frequencies around 10–40 Hz. These overlap with the truck-induced vibration frequencies and may even be within the amplification zone of the foam material. This will cancel out vibration reduction or, worse, add up to catastrophic oscillations on the canvas. The prevention of vibration amplification was only achieved when polyethylene foam (Ethafoam) and polyurethane composite foam were used in their unity zone (Figure 5).

CONCLUSIONS

The results of field and laboratory experiments clearly show that vibration damping with the usual damping materials is difficult to achieve. The amplification zone cannot be pushed sufficiently by simply increasing the static load in order to exclude resonances on paintings. The protective cushioning concept, while successful in reducing shock events, fails to reduce vibration immissions.

A critical aspect in the performance of the complete workflow is the limited control on the practical implementation. Ultimately it is important that each element of the system is inherently stable and there is absolutely no clearance at any of the interfaces. The artwork must be firmly connected with the decorative frame and the backing board. Each individual layer of packing material must be form fitted. Connections between the solid parts must be rigid with no tolerance. The object must be firmly fitted within the system box, which in turn must be tightly fixed within the truck. Only with these conditions fulfilled can materials be employed according to their properties for specific attenuation. The project goal is to arrive at a workable packing solution, maximising the control of the vibration and shock behaviour in all directions.

ACKNOWLEDGEMENTS

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NOTES

1 The measurements of many test canvas paintings themselves and the whole systems including backing board, painting and glazing confirmed the range of 4–50 Hz.

2 The publication of the results is in preparation.

3 The lower limit for ASTM D 4728 was set to 3 Hz. Trapezoidal shocks had a duration of 10 ms with ramps of 2 ms.

4 Several foam products (Plastazote FoamPartners and different polyurethane and composite foams) were tested. Within the different material categories, there were no relevant differences detected.

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MATERIALS LIST

Uniaxial accelerometers, PCB 352A73
Triaxial accelerometer, PCB 356A16
Control element, cRIO, National Instruments
Datalogger MSR 165, MSR Electronics
Shaker, ETS Solutions MPA102/L620M/GT500M

Foam specifications:
Low density polyethylene foam, Ethafoam™ 220, with an approx. density of 33 kg/m^3 (The Dow Chemical Company)
Polyurethane foam, with an approx. density of 22 kg/m^3
Polyurethane composite foam, with an approx. density of 170 kg/m^3, FoamPartner

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