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FRONT COVER:
Caravaggio, *The Supper at Emmaus*
(detail of Plate 4, p. 42)

PAGE 1:
Jan van Huysum, *Hollyhocks and Other Flowers in a Vase* (NG 1001), 1702–20. Detail.
(See Fig. 4, p. 79)

Monitoring Shock and Vibration during the Transportation of Paintings

BY DAVID SAUNDERS

WHEN paintings are sent to other museums or galleries on loan, they are usually packed in rigid, sealed, cases to protect them from environmental and mechanical damage. The principal environmental hazards against which these containers provide protection are extremes of temperature or relative humidity and rapid changes in either of these parameters. In addition, the case serves as a barrier between the painting and chemical and particulate atmospheric pollutants and, if necessary, protects the painting from rain. The causes of mechanical damage can be divided into shocks and vibration: the former are discrete events caused by, for example, collisions, dropping or toppling, while the latter are longer-term effects, usually the result of transmission of vibration from the motor in a vehicle or from a road surface. Most modern packing cases, including those used at the National Gallery, provide an efficient barrier against all but the most extreme external environmental conditions.[1]

The *Art in Transit* conference, held in London in September 1991, served as a focus for research into the behaviour of paintings in response to temperature, relative humidity, shock and vibration, and into the design of suitable packing cases.[2] The papers contained in the conference proceedings outlined recent research in a series of areas. First, the effects of particular environmental parameters on paintings and painting materials were discussed.[3] The conditions likely to prevail during transportation from one venue to the next were then identified.[4] Appropriate packing materials and techniques to cope with these conditions were discussed.[5] Finally, the results of monitoring the conditions within cases during transportation were reported.[6] The effects of temperature and relative humidity and their control and monitoring were covered in great detail, with a remarkable consensus as to the best methods of preventing potential damage to paintings by these agents.

The effect of shock and vibration on paintings is, however, less well understood. Studies of the theoretical response of paint and glue films or canvases suggest that at the level of shock and vibration experienced during transportation, there will be no primary damage to paintings.[7] While these results were borne out by studies on 'real' samples, the paint films used were relatively young and perfect. The authors rightly point out that damage to an aged, already cracked or delaminating film, or secondary damage, caused for example by a canvas impacting on a stretcher bar, cannot be ruled out.[8] Indeed, it is clear from the studies conducted by the Doerner Institut, Munich, that paintings transported under 'normal' conditions not only can, but do, suffer structural damage.[9]

In transit, paintings are generally protected from shock and vibration by means of compressible foam pads attached to the inside of the case. The number and size of these pads are determined from the weight of the painting to be supported and the physical properties of the foam used. The method of calculating the requisite surface area for the cushioning is well-established;[10] too much cushioning can be as disastrous as too little. Assessment of the effectiveness of cushioning in packing cases generally involves standard drop and vibration table tests.[11]

While it is possible to estimate the maximum shock suffered by a case using shock detectors that react to a particular level of acceleration,[12] little monitoring of shock and vibration in cases during transit has been possible, as the equipment required has generally been too bulky to be included alongside the painting in standard packing cases. Clearly, it would be possible to use a larger case to accommodate the equipment, but this would change the characteristics of the packing environment and severely limit the value of the information obtained. In 1990, the National Trust and the National Gallery conducted a study of the shock and vibration experienced by paintings during road transportation using a data logging system developed specifically for this purpose at the Engineering Department of the University of Cambridge.[13]

Although this study successfully examined the merits of different packing methods for road transportation, two drawbacks of the 'Cambridge' logging

equipment became apparent. First, although the equipment was much more compact than other logging systems used to measure shock and vibration in packing cases (some of which have been known to occupy the entire case), the logger and associated amplifier were still rather bulky for inclusion in small or medium-sized cases, particularly those used for hand-carrying paintings between exhibitions. Secondly, the equipment could not be included in shipments that were travelling by air, as it had not been passed for inclusion in aircraft holds because of the risk that it might produce electrical signals that could interfere with the aircraft's systems. The extended programme of logging described in this paper arose out of the possibility of obtaining a shock/vibration logger that overcame these difficulties. The sections that follow describe this logger and a selection of representative results obtained from measurements made during several dozen transportations by road, sea and air.

Equipment and procedure

As intimated above, a more comprehensive analysis of all types of transportation became feasible with the acquisition of a logger that was compact enough to be included in nearly all packing cases, could run on modest power and had sufficient memory to log journeys of several days.[14] These 'Wanderer' loggers measure only 70 × 105 × 25 mm and weigh approximately 140 grammes (including a PP3-type battery). The measurement range is determined by which of four accelerometers is factory pre-fitted. The loggers used by the National Gallery can measure shock/vibration in the range 0–10*g* with a sensitivity of *c.*0.05*g* in the principal axis and, according to the manufacturer, respond to vibration in the 3 to 400Hz range.[15] In all the studies described here, the principal measuring axis was the vertical. The microprocessor in the logger can be programmed to record the peak acceleration during a user-defined measurement period. The record obtained is, therefore, a series of maxima, typically for every 30-second period throughout the transportation. In order to save memory during periods when the input to the accelerometer is constant (usually zero) a new record is not made until the shock/vibration level changes, at which time the new value and the associated time are stored in the memory. As a result, records of long journeys with several protracted stops can be made without the memory filling. Finally, the logger also measures temperature during the same logging period using the same memory-saving principle.

The Wanderer logger offers a less comprehensive record of the shock and vibration than the 'Cambridge' equipment; the latter indicates in which axis the acceleration has occurred and indicates within which of five frequency ranges (0–5 Hz, 5–10 Hz, 10–20 Hz, 20–50 Hz and 50–500 Hz) vibrations fall. By using the two logging systems together in a number of preliminary experiments it was, however, possible to establish in which frequency bands and in which axes the principal shocks and vibrations occurred during transportation. As noted in the previous study, the discrete shocks associated with loading and unloading tend to fall in the low frequency range of the Cambridge logger, 0–5 Hz, while the lower amplitude vibrations that prevail during road transportation fall in the 50–500 Hz range.[16]

To test the logger, a preliminary study was made of an inland transportation by road, from the National Gallery to the City Art Gallery in York. The procedure described here was followed in the other studies described in this paper. Prior to the shipment, the logger was programmed to commence recording shortly before the case was taken from storage to be loaded onto the vehicle. The logger was then attached to the frame before the painting was wrapped in polythene sheeting and packed. All the shipments described in this paper were made using *Dripak* type cases, now supplied by, or leased from, Kent Services Ltd (KSL).[17] On arrival at the destination, the logger was removed and brought back to London by the courier so that the record could be downloaded to a computer for analysis and storage. The results from the transportation to York are presented in Fig. 1. The same format is used in all subsequent figures; shock/vibration in *g* is plotted against time for all or part of the transportation. The accompanying table (Table 1 in this instance) summarises events affecting the cased painting during that portion of the journey. These tabulated records are based on notes made by the courier accompanying the shipment; all National Gallery loans are accompanied by a member of staff. The couriers are asked to note unusual road conditions, problems encountered with loading or unloading and any other event that might feature on the record of shock and vibration.

The shock/vibration trace in Fig. 1 is fairly typical for a road transportation. The loading and unloading were characterised by discrete shocks, with accelerations of up to 2.2*g*. The most intense shock corresponded to unloading, when the (rather heavy) case was carried up steps into the City Art Gallery. During the road journey there was a fairly consistent level of

Table 1 Timings for the transportation from the National Gallery to York City Art Gallery; Titian, *Portrait of a Young Man* (L 611); Case M1 (Dripak)

08:00	Case taken from store to loading bay and secured in vehicle
08:15	Depart from National Gallery
10:25	Stop for coffee
10:55	Journey resumes
13:50	Arrive at York City Art Gallery
13:55	Case unloaded and carried up steps to exhibition area

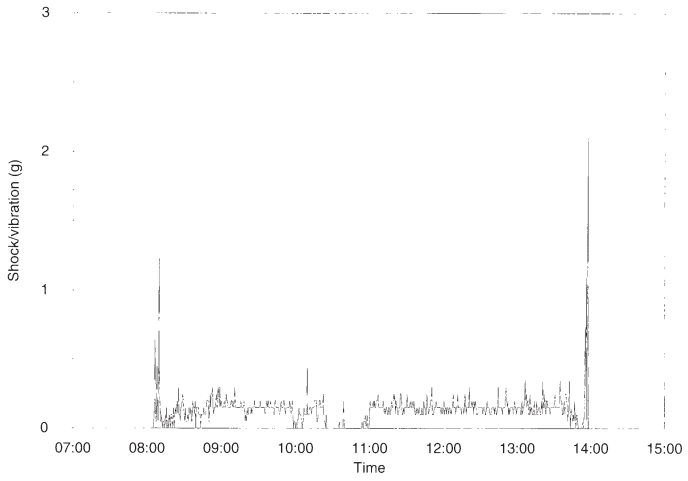

Fig. 1 Shock/vibration record for the transportation from the National Gallery to York City Art Gallery.

Table 2 Timings for part of the transportation from the National Gallery to Fondation Maeght, St Paul; Braque, *Still Life with Glass and Newspaper* (L 499); Case H5 (KSL)

08:05	Case loaded onto vehicle at National Gallery
08:30	Depart from National Gallery
09:25	Stop for petrol
09:40	Journey resumes
10:45	Arrive at Dover docks
11:00	Vehicle loaded onto ferry
11:30	Ferry departs Dover
13:00	Ferry arrives Calais
17:00	Stop

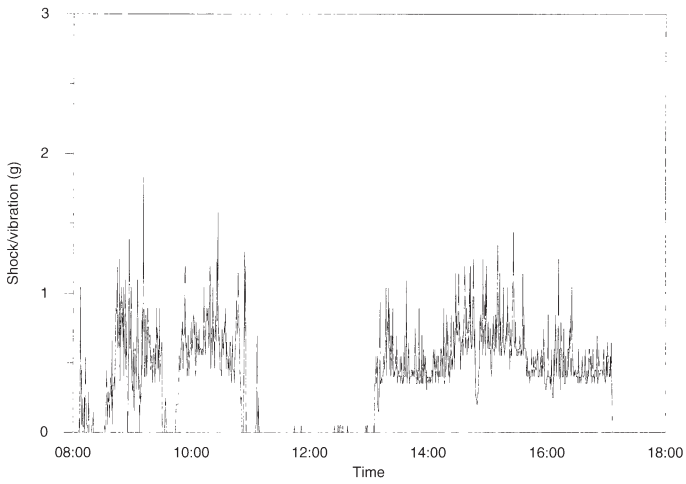

Fig. 2 Shock/vibration record for part of the transportation from the National Gallery to Fondation Maeght, St Paul.

vibration in the 0.2–0.3*g* range, with occasional discrete maxima approaching 0.5*g*. Although the latter may correspond to sections of poor road surface or expansion joints on bridges, it will be seen in the next section that these maxima are comparatively modest. Indeed, subsequent studies have shown that the level of 'background' vibration during the journey to York (0.2–0.3*g*) was at the lower end of the range recorded for road transport. This shipment was made in a vehicle fitted with air-ride suspension and this may explain the low levels, which are of the same order as those measured for cased paintings in air-ride vehicles in the previous study.[18]

Results and Discussion

Following the preliminary study during the journey to York, a number of road transportations to mainland Europe, involving ferry journeys, were recorded. The aim, in part at least, was to acquire comparative data against which to compare information obtained from journeys by air. Such comparisons would inform decisions as to the least potentially damaging mode of transport for a particular shipment, although these data need to be considered in conjunction with other potential environmental risks and issues of security associated with protracted journeys.

Fig. 2 shows the record of shock/vibration accumulated during the transfer of a painting from the National Gallery to the Fondation Maeght at St Paul in southern France. This graph shows only the first day's journey, which included crossing the English Channel by ferry. Table 2 contains a record of events corresponding to Fig. 2; here, as in all the tables and figures, the time given is that in London, rather than local time where this differs.

In contrast to the journey to York, the level of vibration recorded during the road portion of this transportation was in the range 0.5–1.0*g* with occasional maxima up to 1.5*g*. It has become apparent that this higher level of shock/vibration should be considered the norm, rather than the much lower levels measured during the York transfer. On this occasion, loading the case into the vehicle resulted in no shocks greater than *c.* 1*g*. The ferry crossing was characterised by extremely low levels of shock and vibration,

Table 3 Timings for the transportation from the National Gallery to Real Academía, Madrid; Mazo, *Queen Mariana of Spain in Mourning* (NG 2926); Case P1 (KSL)

01:30	Case loaded onto vehicle at National Gallery
01:45	Depart from National Gallery
07:00	Arrive at Plymouth docks
07:45	Vehicle loaded onto ferry
09:00	Ferry departs Plymouth
10:30	Ferry arrives Santander
10:45	Depart from docks
18:00	Arrive at Real Academía
19:05	Case transferred up steps to museum

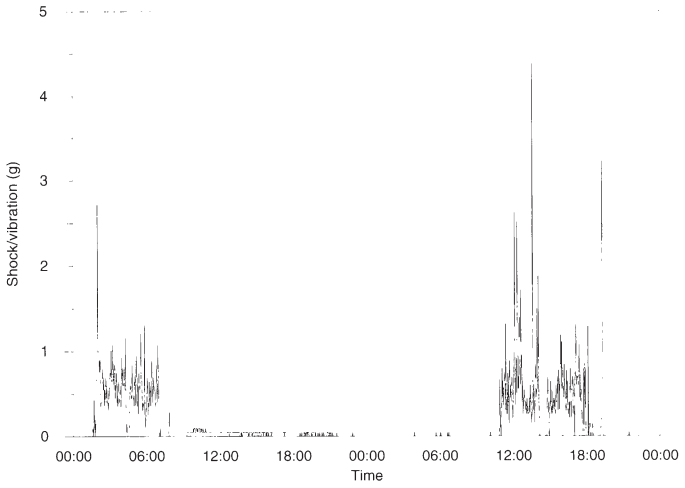

Fig. 3 Shock/vibration record for the transportation from the National Gallery to Real Academía, Madrid.

less than 0.1*g*, and there were no indications of the severe shocks that it had been feared might be associated with loading the vehicle onto the ferry or with disembarkation.

A similar pattern emerged from a much longer ferry crossing, this time from Plymouth to Santander, *en route* from London to Madrid. The shock/vibration measurements during this transportation are shown in Fig. 3; Table 3 contains the corresponding timings. On the journey from London to Plymouth, which was largely on motorways or high-quality roads, the level of vibration was around 0.5–1.0*g* with occasional peaks over 1*g*. These levels were very similar to those measured during the transportation to St Paul and in other road journeys. The level of vibration experienced by the painting after arrival in Spain was considerably greater. Although the shock/vibration level was in the region 0.5–1.0*g* for much of the time, the level often exceeded 1*g* while some isolated shocks of up to *c.*5*g* were recorded. The level of vibration during the ferry crossing was again very low, typically 0–0.05*g* with no notable shocks on loading or unloading. All measurements made during ferry crossings have served to confirm that there is very little shock/vibration associated with this mode of transport, although no shipment has yet been logged during a rough passage. The unloading at the Real Academía in Madrid produced a shock with a magnitude in excess of 3*g*, perhaps while the case was being carried up steps into the museum. Clearly this practice should be avoided whenever possible.

It can be difficult to make comparisons between journeys, as the size and type of case will vary and different vehicles may be used for the transportation. In each instance, however, the packing materials within the case are tailored to the size and mass of the painting to be transported to ensure correct dynamic loading. All the above examples were for transportations in vehicles equipped with air-ride suspension, although no check was made of the adjustment of the suspension to suit the loading of the vehicle. Despite these shortcomings, it has become clear that a 'background' vibration level of around 0.5–1.0*g* can be expected for suitably cased and cushioned paintings during road transport with air-ride vehicles. The overall level of shock and vibration and the strength of the discrete maxima during the road journey can, however, often be related to specific road conditions. The courier accompanying the painting by Mazo (NG 2926) to Madrid noted that the road conditions on the route chosen through northern Spain were very poor. On the return leg of the journey, taking a slightly different route, the discrete shocks associated with a poor road surface were fewer and weaker.

The measurement of shock/vibration throughout journeys made by air was one of the prime aims of this study. As with road transportation, a fairly clear pattern has emerged, well illustrated by the record made during the return of a painting by Sisley (NG 4138) to the National Gallery shown in Fig. 4 and Table 4. Prior to the flight, three distinct periods of vibration were apparent. The first of these corresponded to loading the case into a vehicle at the Museum of Fine Arts, Boston, and its transportation to the cargo area at the airport. Discrete shocks of 1–2*g* characterised loading and unloading from the vehicle. The journey, which was longer than anticipated due to heavy traffic, shows a low 'background' level of shock/vibration, around 0.2–0.3*g*, with some isolated peaks of up to 0.7*g*; the latter were more frequent towards the end of the journey when, off the freeway, the road surface was less good. The second period contained shocks of up to *c.*1*g* and corresponded to the period during which cases were placed on the pallet. The final period of shocks prior to take-off was approximately one

hour before departure and was due to transport to, and loading onto, the aircraft. Although the shocks experienced here were, as on other occasions, greater than those in the cargo shed when the painting was under the direct supervision of the courier, they were less than those sometimes experienced at this stage, which can be up to 8–9*g*.

The period after landing was again characterised by three periods of activity, analogous to those above. Unloading from the aircraft and transfer to the cargo area showed fewer shocks than loading and the maximum is slightly lower, *c*.1.5*g*. In the cargo shed, the maxima were slightly higher than during loading, with several peaks of *c*.2*g*. Finally, the road journey to the National Gallery shows a typical pattern of shock/vibration with a 'background' level of 0.3–0.4*g*.

Like ferry journeys, the flight itself shows little shock or vibration, with small peaks on take-off and landing, around 0.1*g* in this instance. This pattern has been repeated in all the air journeys logged, with the shocks on take-off and landing, which are generally in the 0.1–0.3*g* range, often serving as the only indication of the flight period.

The measurements presented thus far serve to illustrate the different shock/vibration patterns that characterise various modes of transportation. The acquisition of a second 'Wanderer' shock/vibration logger offered the opportunity to assess the effectiveness of the cushioning systems and to make comparisons between cases. Examples of these ongoing comparative experiments are given here. In the first of these studies, one logger was secured to the frame of Veronese's *The Consecration of Saint Nicholas* (NG 26), and a second logger was attached to the nearest point on the inner skin of packing case ILP-143, in which this painting was to be transported to the Chrysler Museum in Norfolk, Virginia. Both the outward and return journeys were logged: Fig. 5 shows part of the shock/vibration record made during the return of the painting from Norfolk, Virginia, via New York, Amsterdam, Hook of Holland and Harwich.[19] The measurements made during this transportation, which were broadly similar to those made during the outward journey, provided information on the cushioning properties of the case during road, air and ferry travel.

A comparison between the data recorded for the painting and those recorded for the case makes clear the role of the packing materials in shock/vibration damping. The skin of the case, to which the second shock and vibration logger was attached, shows peaks of up to *c*.9*g*, while the maximum shock experienced

Table 4 Timings for the transportation from the Museum of Fine Arts, Boston, to the National Gallery; Sisley, *The Watering Place at Marly-le-Roi* (NG 4138); Case 3.2 (Dripak)

19:45	Case moved to loading bay
19:55	Case loaded onto vehicle
20:00	Depart from Museum of Fine Arts, Boston
21:30	Arrive at cargo area, Logan Airport
22:20	Case placed on pallet
22:50	Pallet taken from cargo shed to waiting area
01:15	Take-off
06:55	Landing at Heathrow Airport, London
08:50	Other items removed from pallet
09:15	Case removed from pallet
09:55	Case taken to secure store
11:05	Case loaded onto vehicle
11:10	Depart Heathrow
12:20	Arrive National Gallery
12:25	Case taken to secure store

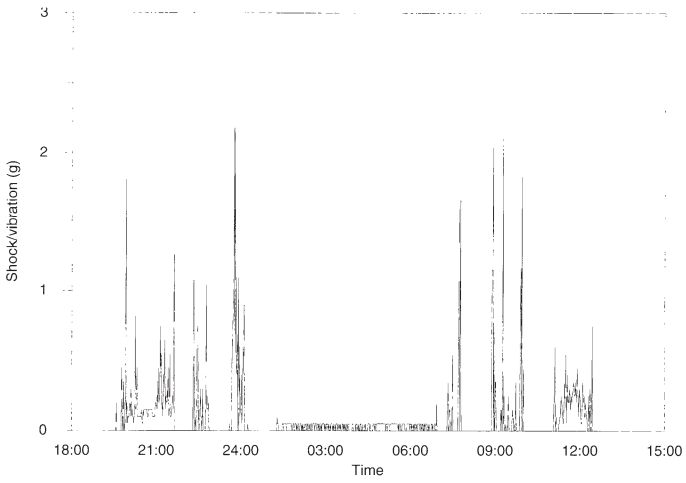

Fig. 4 Shock/vibration record for the transportation from the Museum of Fine Arts, Boston, to the National Gallery.

by the painting is less than 3*g*. Although the profiles of the two traces are similar, the degree of damping is not uniform, suggesting that the packaging is best suited to reducing certain types of shock/vibration. In particular it is evident that the cushioning material attenuates discrete shocks more effectively than it reduces the transmission of 'background' vibration during road travel.

The level of shock and vibration measured at the painting was at the lower end of the range detected in previous transports. Although there were one or two shocks of just over 2*g* during the movement of the packing case through the cargo handling areas at the airports, the loading and unloading in New York and Amsterdam respectively were characterised by a series of peaks of 1–2*g*. The road journey from Washington to New York shows a fairly continuous level of vibration in the 0.5–0.8*g* range, with rather

higher levels towards the end of this journey, as the vehicle approached the airport. In contrast, vibration levels during the road journeys from Amsterdam to Hook of Holland and from Harwich to London (not shown in Fig. 5) are much lower, <0.5*g*. This pattern of behaviour has been noted on several occasions: when cased paintings have been moved by road in both Europe and the United States, the level of vibration has been generally somewhat higher in the latter, although it has not proved possible to determine whether this was due to poorer road surfaces, less efficient suspension or positioning within the vehicle. The level of vibration during the flight and ferry crossing (not shown in Fig. 5) was again negligible; although the peaks corresponding to take-off and landing are quite clear in the record from the logger attached to the case.

The second type of comparison made using identical loggers was that between paintings travelling between exhibition venues in the same shipment, but in very different size packing cases. The general trends observed under these circumstances are most conspicuous in the example illustrated in Fig. 6. The National Gallery lent a number of paintings to the *Glory of Venice* exhibition in 1994. For the transfer of the loans from the Royal Academy in London to the National Gallery of Art in Washington, loggers were attached to paintings of very different size. One logger was fixed to Canaletto's *Venice: The Feast Day of Saint Roch* (NG 937), the other to Guardi's *An Architectural Caprice with a Palladian Style Building* (NG 2517); these paintings have dimensions of 147.7 × 199.4 cm and 22.3 × 17 cm respectively. The two cases used in the transportation, although very different in size, were fitted with appropriate cushioning for the dimensions and weight of the paintings within. In Fig. 6, the records of shock/vibration from the two loggers for that part of the transportation from London to Washington detailed in Table 6 are plotted using the same time axis (note, however, the discontinuity in the time axis between 19:00 on the first day and 07:00 the next).

From these results it was clear that the level of shock/vibration suffered by the Canaletto was consistently lower than that experienced by the Guardi. Both cases contained comparatively thick layers of shock-absorbing foam at the top and bottom, but the case containing the Guardi was smaller and of a type designed to accommodate two paintings. It may be that the thinner layers of foam needed to allow two paintings to fit in a single case proved less effective in cushioning shock. The difference between the two cases is most noticeable during loading and unloading, particularly at the airport in Paris[20] and during the road journey in the United States. At the airport in Paris the painting in the smaller case received discrete shocks of over 6*g*, while the larger painting suffers no shock greater than *c*.1.2*g*. As in previous experiments, the shock and vibration measurements during the ferry crossing and flight were very low for both cases.

Table 5 Timings for part of the transportation from the Chrysler Museum, Norfolk, Virginia, to the National Gallery; Veronese, *The Consecration of Saint Nicholas* (NG 26); Case ILP-143

15:30	Vehicle departs from overnight storage area
16:30	Stop for petrol
16:50	Journey resumes
17:00	Rough section of road
17:50	Stop for petrol
18:05	Journey resumes
19:20	Heavy traffic
20:05	Arrive at cargo shed at JFK Airport, New York
22:30	Case unloaded from vehicle
01:05	Case loaded onto pallet
02:00	Loading onto pallet completed
05:30	Take-off
11:10	Landing at Schiphol Airport, Amsterdam
11:40	Pallet unloaded using forklift and taken to loading bay
12:45	Loaded onto vehicle and depart Schiphol Airport
13:15	Stop for lunch
13:40	Journey resumes
14:50	Arrive Hook of Holland ferry terminal

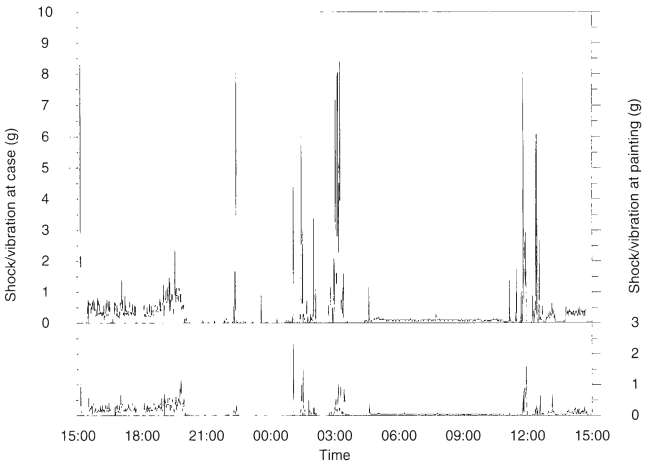

Fig. 5 Shock/vibration record for part of the transportation from the Chrysler Museum, Norfolk, Virginia to the National Gallery: the upper trace is from the logger attached to the case, the lower trace is from the logger attached to the painting.

Table 6 Timings for part of the transportation from the Royal Academy, London, to the National Gallery of Art, Washington; Canaletto, *Venice: The Feast Day of Saint Roch* (NG 937), Guardi, *An Architectural Caprice with a Palladian Style Building* (NG 2517); Cases A/B-1 (KSL) and M1 (Dristyle) respectively

07:30	Cases loaded at Royal Academy
12:30	Vehicle loaded onto ferry
14:15	Vehicle unloaded from ferry
16:10	Vehicle leaves autoroute
18:45	Arrive at Chenue warehouse, Paris – speed bumps
19:00	Vehicle parked for night
07:30	Depart Chenue warehouse – speed bumps
08:05	Arrive Charles de Gaulle Airport, Paris
09:05	Cases moved in cargo shed – placed on pallets
15:05	Pallet loaded onto aircraft
17:30	Take-off
00:30	Landing at New York
02:45	Case removed from pallet
03:25	Case loaded onto vehicle
09:55	Arrive at National Gallery of Art, Washington, unloading

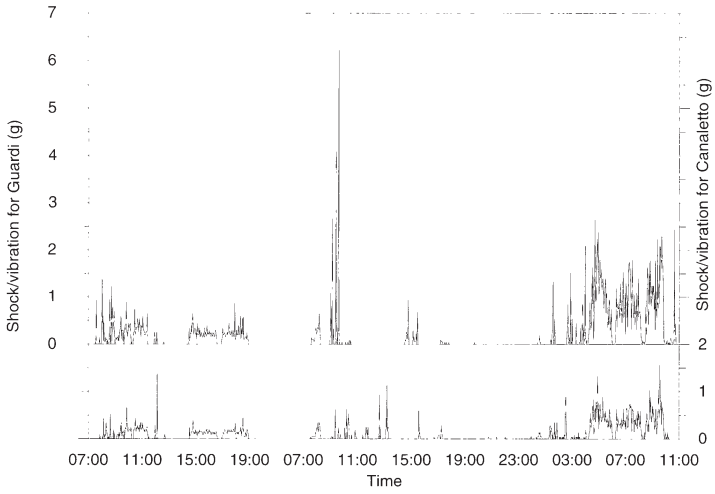

Fig. 6 Shock/vibration record for part of the transportation from the Royal Academy, London, to the National Gallery of Art, Washington: the upper trace is from the logger attached to Guardi's *An Architectural Caprice with a Palladian Style Building* (NG 2517), the lower trace is from the logger attached to Canaletto's *Venice: The Feast Day of Saint Roch* (NG 937). Note the discontinuity in the time axis during the first overnight period.

A second point of interest is that there is again a marked difference between the levels of shock/vibration experienced by the paintings on either side of the Atlantic. For the Canaletto, the 'background' level of vibration during the road portion of the journey from London to Paris was 0.2–0.4*g*; the roads in France were slightly better. In contrast, the level for the road journey from New York to Washington was 0.5–0.7*g*. The corresponding figures for the Guardi were 0.3–0.5*g* in Europe and 0.8–1.3*g* in the United States. The type of vehicle used, the road surfaces encountered or a combination of these factors again seem the most likely causes for this anomaly.

When these two paintings returned to the National Gallery from Washington, a similar exercise was undertaken which confirmed the results of the outward journey. The higher levels of the discrete shocks suffered in the cargo areas at the airport suggested that the smaller case was handled with less care than its larger travelling companion. It seems likely that the large case forces those loading, unloading or palletising the painting to give more forethought to its handling; as a result, it may be handled more carefully than the lighter, smaller case.

Small paintings of the size of the Guardi studied during the transportation to Washington and back are often transported in hand-carry cases, accompanying the courier in a vehicle and in the cabin of an aircraft. The courier is thus able to supervise the entire transportation, a situation that is no longer possible with the tight security restrictions in the 'airside' regions of cargo areas. It might be expected, therefore, that the shock/vibration suffered by a painting carried by the courier would be less than that for a painting travelling as cargo. A number of hand-carry shipments, mostly by road and air, have been studied. The transportation from London to Amsterdam illustrated in Fig. 7 is typical; the corresponding timings are given in Table 7.

The shocks and vibration experienced when the painting in its case was loaded onto the vehicle in London and unloaded at the Van Gogh Museum are similar to those previously recorded for larger cases during these operations; there are also shocks of 2–3*g* each time the case is picked up or put down, for instance at customs or security checks, and of 1.0–1.5*g* when the case is secured in the aircraft's cabin. The shock and vibration caused by movement of the aircraft on the ground is *c.*0.3*g*, while in the air there is little shock, except on take-off and landing, which are both characterised by discrete shocks of *c.*1*g*.

The road journeys from the National Gallery to the airport and from the airport to the Van Gogh Museum both show higher levels of shock/vibration than in other road journeys which have been monitored; neither of the vehicles used for these transfers was fitted with air-ride suspension. Comparing the levels of shock and vibration on the road journey from the Gallery to Heathrow Airport with numerous other records for the same journey made in vehicles

Table 7 Timings for the transportation from the National Gallery to the Van Gogh Museum, Amsterdam; Puvis de Chavannes, *A Maid combing a Woman's Hair* (NG 3267); Case RJ30 (KSL, hand carry)

09:45	Case taken from store to loading bay and secured in vehicle
09:55	Depart from National Gallery
10:35	Arrive at Heathrow Airport
10:40	Check in at KLM desk
10:55	Move to Customs
11:10	Move to Security check
11:25	Taken by 'buggy' to KLM lounge
12:25	Taken by 'buggy' to KLM gate
12:45	Board coach for journey to aircraft
12:50	Case secured in aircraft
13:00	Taxi to runway
13:10	Take-off
13:45	Landing at Schiphol Airport, Amsterdam
13:50	Taxi to terminal
14:00	Case moved on trolley through airport
14:10	Trolley moved across rough surface to waiting vehicle
14:15	Depart airport
14:35	Arrive at Van Gogh Museum

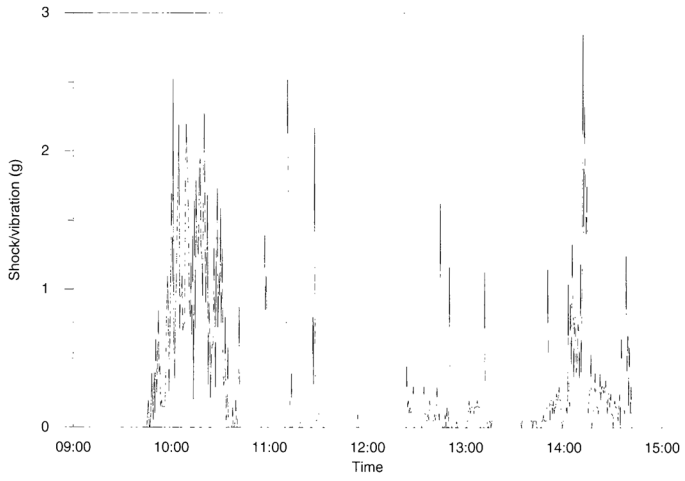

Fig. 7 Shock/vibration record for the transportation from the National Gallery to the Van Gogh Museum, Amsterdam.

fitted with air-ride suspension, it may be concluded that this case/vehicle combination is much less effective in attenuating shock and vibration, suggesting that the design of hand-carry cases and the arrangements made for their transportation do not necessarily offer less shock/vibration than might be expected if a small painting were sent by air cargo.

Conclusions

The study of several dozen transportations that has been summarised in this paper provides an insight into the pattern of shock/vibration which is experienced by cased paintings in transit. Because of the lack of information on the effects on 'real' paintings, it is not possible to define safe limits for shocks and vibration. Although none of the paintings monitored during transportation has shown any visible sign of damage, despite exposure to discrete shocks of up to 10*g* and to high frequency (>50Hz) vibrations at a level of *c.*1*g* for periods of up to six hours, there exists the possibility that structural weakening of the paint, ground or support may not become evident until later. Repeated loans of the same painting could cause a cumulative weakening of the structure. In view of this, it seems prudent to minimise shock and vibration by appropriate casing and careful planning of the journey. There are clearly danger points during the transportation, including loading and unloading at museums, particularly if awkward corners or steps must be negotiated. Handling and palletisation in airport cargo areas also results in discrete shocks which may approach *c.*10*g*; the most severe shocks are frequently encountered once the courier no longer has sight of the case, confirming that the presence of a courier is often a deterrent to careless handling.

Rather unexpectedly, both air and sea transportation result in negligible shock/vibration levels at the painting. Given the choice between transporting a painting from London to continental Europe by road and ferry or by road and air, the decision will rest on the relative damage caused to a particular painting by the different patterns of shock/vibration experienced. The land and sea transportation will result in a longer period of 'background' vibration in the range 0.5–1.0*g*, while the land and air shipment will be on the road for less time but will probably be exposed to shocks of 3–8*g* in the cargo areas at airports. Although most road journeys are characterised by 'background' vibration levels in the range 0.5–1.0*g*, it has been seen that this figure varies considerably according to the case, vehicle and road surface. A more detailed study of these parameters is under way, investigating the properties of different casing systems, looking more carefully at the suspension systems fitted to vehicles – including the effect of incorrect adjustment of air-ride suspension mechanisms – and assessing the effect that the position of packing cases within the cargo compartment of vehicles has on the shock and vibration felt by the painting.

Despite their bulk, larger cases appear to be handled more carefully; small cases in the same shipment suffer greater shock/vibration. The solution for small paintings might be to use a hand-carry case, but it is clear that the shock and vibration suffered by

paintings transported in this way can be nearly as high as in a cargo shipment. Two factors contribute to this. First, hand-carry cases are often transported to and from airports in vehicles with poor suspension systems. Second, because many hand-carry cases are small versions of standard packing cases, they are in practice sometimes too large or too heavy to be carried by hand. As a result, the case is not handled with such care and may be moved over uneven floors on unsuitable luggage trolleys. A project to design lighter, smaller hand-carry cases that will continue to provide adequate shock, vibration and climatic buffering is in progress.

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Notes and references

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6. D. Saunders, 'Temperature and Relative Humidity Conditions Encountered in Transportation', cited in note 4, pp. 305–6; D. Saunders, C. Leback Sitwell and S. Staniforth, 'Soft Pack – The Soft Option?', *Art in Transit: Studies in the Transport of Paintings*, cited in note 2, pp. 311–22.
7. M.F. Mecklenburg and C.S. Tumosa, 'An Introduction into the Mechanical Behavior of Paintings under Rapid Loading Conditions', cited in note 3, p. 149; S. Michalski, cited in note 3, p. 238.
8. See for example, S. Michalski, cited in note 3, p. 241.
9. A. Burmester and M. Müller, 'The Registration of Transportation Damages using Digital Image Processing', *Zeitschrift für Kunsttechnologie und Konservierung*, 6, 1992, pp. 335–45; A. Burmester, M. Müller and F. Schwemer, 'Locating Transportation Damages by Digital Imaging : Two Case Studies', *International Council of Museums Committee for Conservation, 9th triennial meeting*, Washington DC 1993, pp. 401–5.
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12. Simple shock detectors sensitive to different shock levels are available under such names as *Drop'n'Tell* and *Shockwatch*. See S. Staniforth, 'Packing: A Case Study', cited in note 1, pp. 60–1.
13. The equipment used for these logging experiments and the results of these tests are described in D. Saunders, C. Leback-Sitwell and S. Staniforth, 'Soft Pack – The Soft Option', cited in note 6, pp. 313–20. The logging equipment was developed in collaboration with the Engineering Department of the University of Cambridge, particularly Dr Jim Woodhouse.
14. 'Wanderer' loggers were drawn to our attention by Jørgen Wadum, chief conservator at the Mauritshuis, who also supplied us with information from his early logging experiments. The Wanderer WST10/3 loggers used in this study can be obtained from Noreltek KY, Jamytie 2, 96910 Rovaniemi, Finland.
15. The magnitude of the shock or vibration experienced by a painting is expressed as acceleration, and is given in the units *g*, where *g* represents the acceleration due to the earth's gravitational field, equivalent to $9.81 ms^{-2}$. The calibration of the three 'Wanderer' loggers used at the National Gallery was checked in the Engineering Department at Cambridge University using an input of known frequency and amplitude. An input of 1*g* at 30, 50, 80, 100 and 150 Hz gave recorded amplitudes in the principal axis (averaged over one minute) of 0.94, 1.1, 1.08, 1.11 and 1.03*g* for logger 1; 0.93, 1.1, 1.05, 1.03 and 1.06*g* for logger 2; and 0.97, 1.08, 1.07, 1.01 and 1.06*g* for logger 3. Inputs of 1, 2, 4, and 8*g* at 150 Hz were applied, resulting in average recorded values of 1.08, 2.11, 3.93 and 8.25*g* for logger 1; 0.98, 1.88, 3.94 and 7.88*g* for logger 2; and 1.03, 2.07, 4.04 and 8.24*g* for logger 3. When the vibration is applied at 90° to the principal axis, the signal is attenuated; the attenuation is greatest at frequencies ≤50 Hz.
16. D. Saunders, C. Leback-Sitwell and S. Staniforth, 'Soft Pack – The Soft Option', cited in note 6, pp. 317–20.
17. The design of Dripak cases is described in note 1. Those cases not owned by the National Gallery were leased from Kent Services Ltd, Unit 3, Phase 2, Grace Road, Sheerness, Kent ME12 1DB, UK.
18. During the previous study, the record made for a painting packed in a Dristyle case and transported in an air-ride vehicle indicated a 'background' vibration of around 0.1–0.2*g* in the 50–500 Hz band; see D. Saunders, C. Leback-Sitwell and S. Staniforth, 'Soft Pack – The Soft Option', cited in note 6, pp. 318–20.
19. Since there was no direct flight from the UK to the US capable of accommodating a case of this size, the shipment was made via Amsterdam, to take advantage of the freighter service between New York and Amsterdam.
20. As the case containing Canaletto's *The Feast Day of Saint Roch* (NG 937) was too large for any direct flight to the US, this shipment was made by way of Paris.