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DESIGN OF A VIBRATION DAMPING SYSTEM FOR SCULPTURE PEDESTALS: AN INTEGRAL OBJECT-BASED APPROACH

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ABSTRACT

An integral object-based approach is described for designing a damping system to protect a contemporary sculpture exhibition from the effects of vibrations due to heavy construction near the temporary quarters of the Stedelijk Museum Amsterdam. The design was based on the experimental determination of vibration limits of real "deaccessioned" objects provided by the artists, and expected maximum vibration levels based on local building codes. Damping was successfully provided by industrial grade springs selected based on such results. The springs were fixed under the sculpture pedestals, taking the aesthetics of the exhibition into consideration. The results show that the proper protection of objects of cultural heritage is possible if there is reliable data on both the vibration levels to which the objects will be exposed, and their effect on those objects. Such an integral approach also provides a better basis for cooperation between construction companies and collection managers.

RÉSUMÉ

Une approche intégrale basée sur l'objet est décrite pour concevoir un système d'amortissement destiné à protéger une exposition de sculpture contemporaine contre les effets des vibrations dues à d'importants travaux de constructions à proximité des locaux temporaires du Stedelijk Museum Amsterdam. La conception a reposé sur la détermination expérimentale des limites de vibration de vrais objets « retirés de l'inventaire » fournis par les artistes, et sur les niveaux de vibrations maximaux attendus d'après le code du bâtiment local. Des ressorts de type industriel compatibles avec ces résultats ont procuré un amortissement efficace. Les ressorts ont

INTRODUCTION

Heavy construction projects in or near museums are one of several sources of vibrations which can affect the condition of objects. Although the effect of vibrations has been discussed for years, there is still a lack of understanding in the cultural heritage world of what vibrations are, and a lack of understanding of and reliable data on the relationship between vibration levels and object damage. This continues to lead to considerable discussion and irritation for all parties involved when determining allowable vibration levels or developing methods to mitigate their effects. This applies not only to vibrations caused by construction, but also by transport, (rock) concerts and other sources.

In 2006, work began on the renovation of the Stedelijk Museum Amsterdam at its Museumplein location. At that time, part of the collection and a number of special exhibitions could be viewed at the former post and telecommunications building (PTT Post building) near the main train station (see Figure 1). That

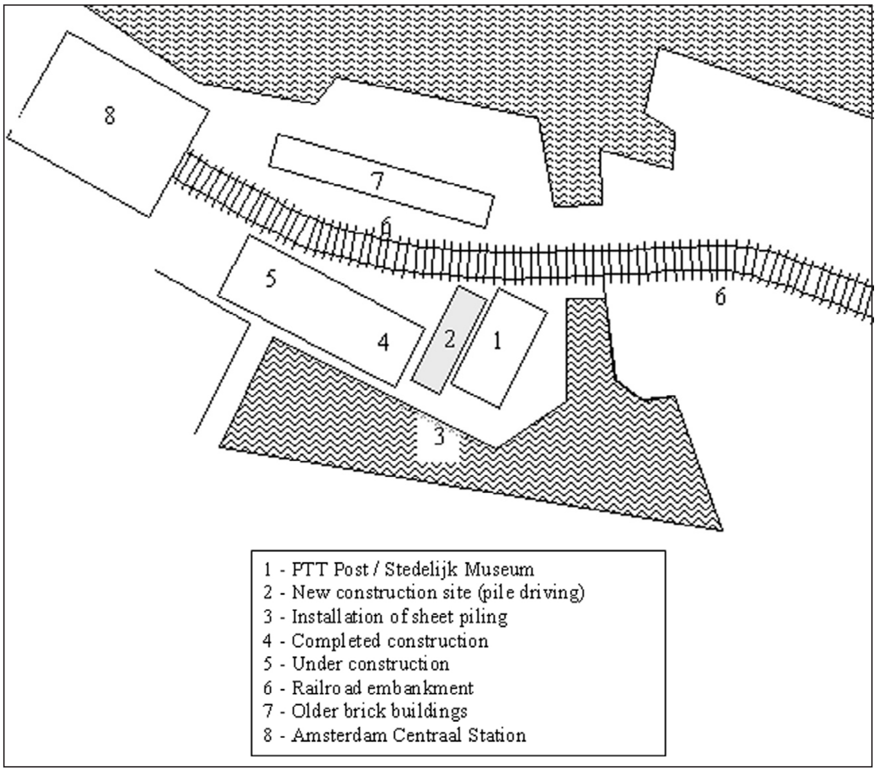

Figure 1
Development area around the temporary quarters of the Stedelijk Museum Amsterdam in 2007

été fixés sous les socles des sculptures, sans pour autant négliger l'aspect esthétique de l'exposition. Les résultats ont montré qu'une protection efficace d'objets du patrimoine culturel est possible lorsqu'il existe des données fiables concernant les niveaux de vibration auxquels les objets seront exposés, et leur effet sur ces objets. Ce type d'approche intégrale favorise par ailleurs la coopération entre les entreprises du bâtiment et les gestionnaires des collections.

RESUMEN

Se describe un acercamiento integral basado en el objeto para diseñar un sistema de amortiguación que proteja una exposición de escultura contemporánea de los efectos de las vibraciones debidas a los trabajos de construcción cercanos a las instalaciones temporales del museo Stedelijk de Ámsterdam. El diseño se basó en la determinación experimental de los límites de vibración de objetos reales "dados de baja", proporcionados por los artistas, y de los niveles máximos de vibración esperados basados en códigos locales de construcción. La amortiguación se consiguió de manera exitosa por medio de resortes de uso industrial seleccionados con base en dichos resultados. Los resortes se fijaron debajo de los pedestales de la escultura, considerando la estética de la exposición. Los resultados muestran que una protección adecuada de objetos del patrimonio cultural es posible si hay datos fiables tanto de los niveles de vibración a los que se van a exponer los objetos, como de su efecto sobre dichos objetos. Un enfoque integral como este también proporciona mejores bases para la cooperación entre las empresas de construcción y los gestores de las colecciones.

location continues to be part of a major development project. In the fall of 2007, the museum was confronted at short notice with the prospect of the start of heavy construction work on a new building right next door. In fact, pile driving would take place as close as three meters from the building, this in addition to the installation of sheet piling along the harbour. During this time, a special exhibition of sensitive contemporary sculpture by the Dutch artists Liet Heringa and Maarten van Kalsbeek was planned. Concerns were thus raised about possible damage to the exhibition.

The Cultural Heritage Agency of The Netherlands (RCE, formerly ICN) and the Stedelijk Museum cooperated on the design of a damping system for the pedestals in order to protect the sculptures, 17 in total, from damage. An integral approach was taken, working with the designer of the pedestals for the sculptures, a civil engineering consultant, a vibration testing facility and manufacturer of industrial grade springs, and a manufacturer of foam damping materials in order to arrive at a solution. The results of this work are presented here and the implications of such an integral approach are discussed.

A NOTE IN ADVANCE – DEFINITIONS

The considerable confusion in the cultural heritage world over how to deal with vibrations and their effect on (sensitive) objects is due in large part to a lack of understanding of the terminology, caused in part by the poor translation of vibration measurements to cultural heritage applications by vibration engineers. For the purposes of this paper and future work on vibrations, the following concepts need to be properly understood.

Vibrations

Vibrations are a form of cyclic (repeated) loading and occur over "long" periods of time (see Figure 2 c). Vibrations, and cyclic loads in general, are described by an amplitude (the strength of the vibration) and a frequency (in cycles per second; one Hertz is one cycle per second). The amplitude can be given, for example, as a deformation amplitude, such as how far a painting canvas moves back and forth in the frame as it vibrates.

Damage due to cyclic loads (fatigue damage) can occur at levels far below the strength of the materials involved. It begins on a micro-scale and is cumulative in nature, often growing unseen until the object "fails", e.g. a crack appears, a piece of paint falls off, etc. This means that it is not enough just to know how strong the vibrations are, but also how long they last (how many cycles – the dose). This is a similar concept dealt with in light aging (one must know both the light intensity and the dose – time of exposure).

Resonance

Objects vibrate at all frequencies. However, depending on their geometry, weight, and the materials they are made of, there are a few frequencies

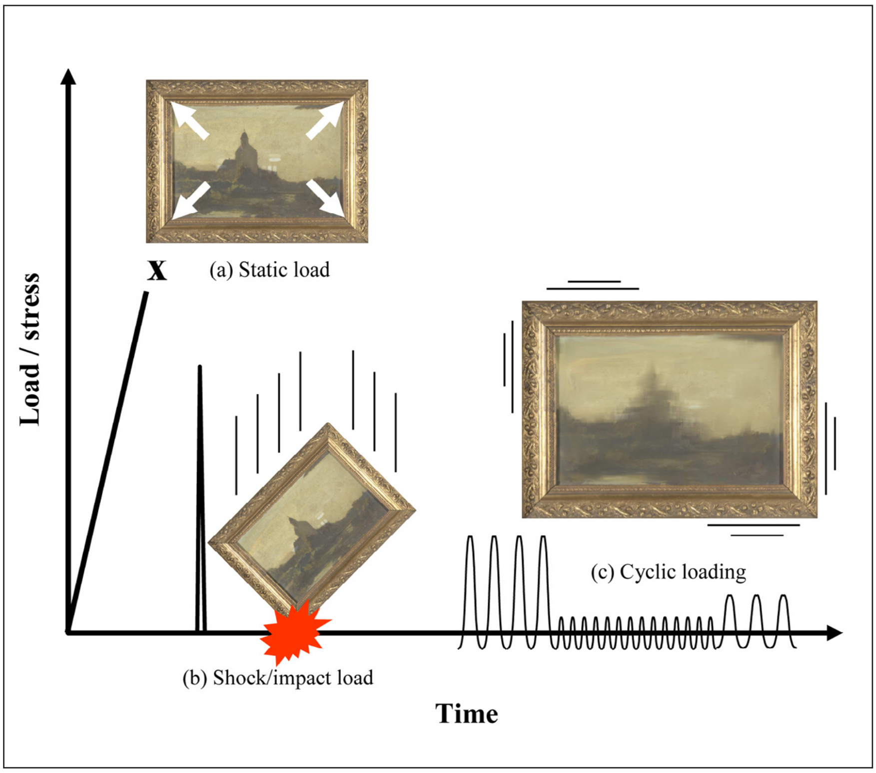

Figure 2
Three types of mechanical loading on objects using paintings as an example

where an object will vibrate almost uncontrollably. These are the so-called resonant frequencies. In terms of damage, these are the worst offenders. However, lower amplitude vibrations at other frequencies, known as forced vibrations, can also cause cumulative damage, though it takes much longer.

Vibration level/intensity

Vibration levels are generally measured and given in terms of a velocity (e.g. in millimeters per second [mm/s]), or an acceleration or g-force (e.g. in millimeters per second per second [mm/s^2]). Acceleration and g-force are actually more related to shock loading. While such values give some indication of vibration intensity, they cannot be used, as such, for relating vibration levels to object damage. Without going into the mathematical details, velocity or acceleration values are a combination of the amplitude (intensity) and frequency. High velocity does not necessarily mean high intensity. The frequency at which the velocity was measured must also be known in order to establish the intensity. In this paper, velocity and frequency values are used together.

However, it should be noted that in order to relate vibration levels to damage, vibration levels need to be given in units of stress or strain (deformation) amplitude, e.g. the motion of a canvas in mm. Information about the properties of the object, such as weight, construction, materials, etc. is also necessary.

Shock

Shock is a single, high-speed impulse load such as the dropping of a painting (see Figure 2 b). If the load is high enough, it can cause immediate damage. Damage occurs roughly around the material strength of the object.[1] Right after the shock, there is a short period of "after-shocks" which engineers call vibrations. These are, indeed, vibrations, but make up only a very small part of all the vibrations an object can be exposed to during transport, due to construction work, etc. Virtually all measurements of "vibration" to date ignore vibrations and are actually measurements of "shock".

THE "CURRENT" SITUATION

The situation which the Stedelijk Museum faced is common for museums having to deal with vibrations due to construction work. This situation can be visualized using the diagram shown in Figure 3(a). The contractor wants and needs to do his work using specific kinds of equipment, according to some kind of time schedule. In The Netherlands, the contractor is subject to Dutch guidelines (SBR – Part A) for "Damage to Buildings" due to vibrations (Waarts and Ostendorf 2006). These guidelines define how much "load" can be put on the neighboring buildings, that is, vibration and shock levels are defined for specific types of building construction.

On the other side of the wall, the museum feels threatened and asks the contractor to limit the amount of vibrations produced. However, herein lies the crux of the problem in the cultural heritage world. There are no standards

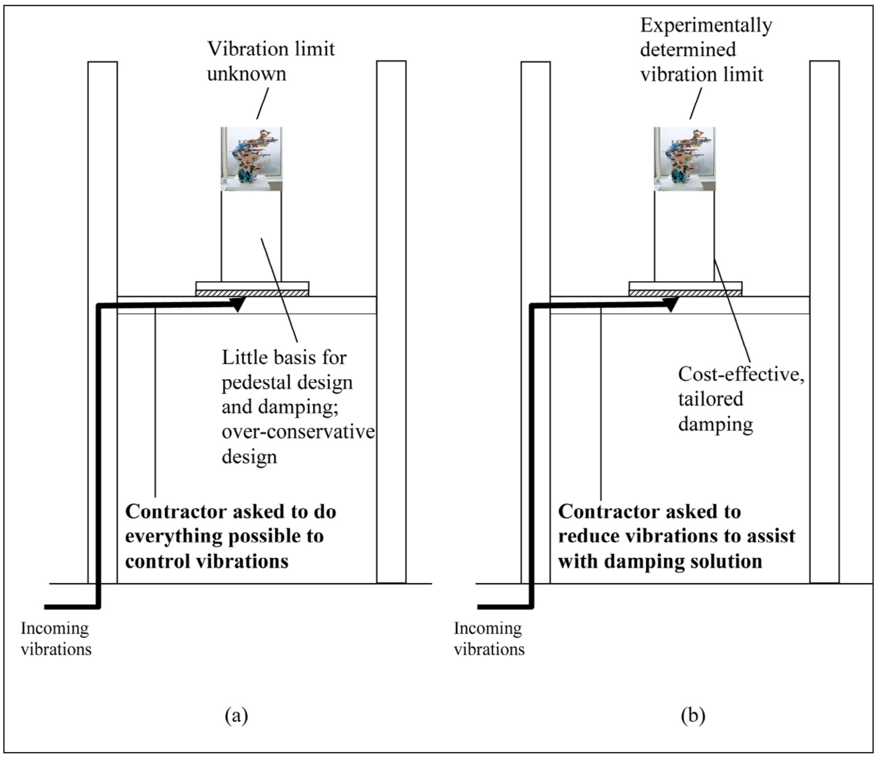

Figure 3
Schematic diagram of ways for dealing with vibrations near a museum due to construction work
a) The current way, where the contractor must bear the burden of vibration mitigation
b) Integral approach, where the contractor and museum can share responsibility for vibration protection

for vibration levels related to objects, and there is, in fact, virtually no data available for defining vibration limits for any kind of object. Except for limited studies on paintings (Staniforth 1984, Mecklenburg 1991, Saunders 2005, and Wei et al. 2005), no systematic scientific study has ever been conducted on the relationship between vibrations and damage to specific types of objects. This means that conservators, conservation scientists and curators have to set limits based on limited practical and anecdotal evidence and their own gut feelings and value judgements. This makes negotiations with a contractor extremely difficult, since the museum must take a very conservative (no pun intended) standpoint. Furthermore, it makes it difficult to determine what measures can be taken to protect specific endangered objects or collections. In this type of situation, the burden of vibration protection lies more on the shoulders of the contractor.

For the current project, an integrated approach was taken. Using this approach, the following aspects of the problem were incorporated as far as possible:

1. determination of the levels of vibrations expected in the museum
2. experimental estimation of the allowable vibration level for the objects
3. design of a damping system for the objects.

In this way, an attempt was made to find a better balance of responsibilities for the protection of the exhibition.

VIBRATION LIMITS BASED ON BUILDING CODES

In the present case, the notice given to the museum about the upcoming work was too short for meaningful contact with the contractor. The best line of action, therefore, was to determine what the contractor would face in terms of vibration limits related to building integrity.

The PTT Post building is basically a reinforced concrete building. According to the Dutch SBR guidelines, this is a so-called Category 1 building for which relatively high levels of vibration are permitted. However, referring again to Figure 1, there are a number of older brick buildings very close by, which fall under Category 2 with lower allowable vibration levels. Furthermore, the railroad tracks leading to Amsterdam Central Station run along a dike (embankment) behind the PTT Post building. A previous court judgment also limits the vibration levels near the railway embankment to Category 2.

The guideline for Category 2 is shown in Figure 4 as a graph of vibration level in mm/s on the vertical axis, versus frequency on the horizontal axis. The red line shows the vibration limits for each frequency. For example, at 10 Hertz (Hz), the vibration level may not exceed 2 mm/s; this limit then increases to around 6 mm/s at 50 Hz and to a little more than 8 mm/s at 100 Hz.

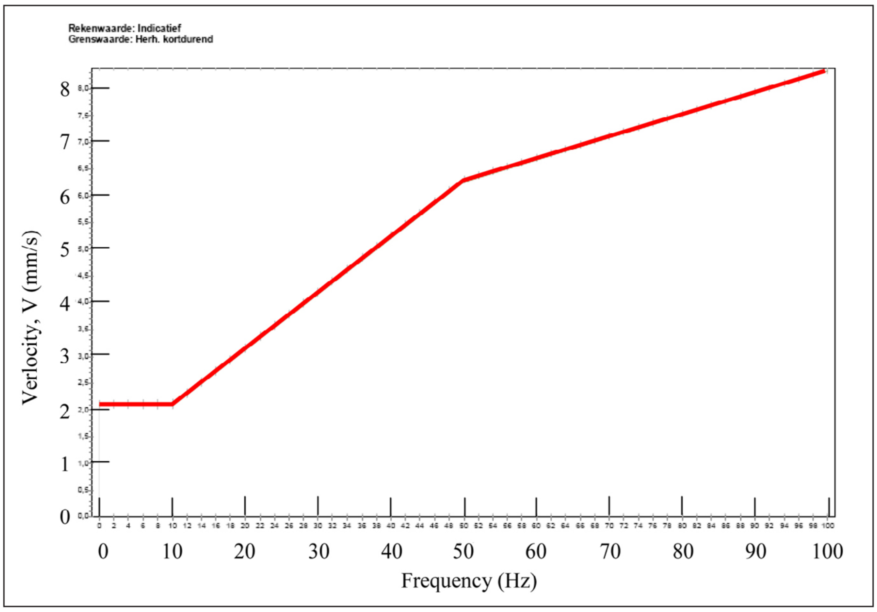

Figure 4
Limits to vibration levels to the PTT Post building as calculated from Waarts and Ostendorf (2006)

VIBRATION LIMITS BASED ON OBJECT TESTING

Vibration testing was conducted on a real but "deaccessioned" object provided by the artists in order to determine whether or not it would be damaged during the time the exhibition would be exposed to the heavy construction work. It should be noted that this object only gives an indication of how the collection would behave. The object was placed on a vibration table in the laboratory of Sebert Trillingstechniek B.V., Bergschenhoek, The Netherlands (see Figure 5). It was not firmly fixed to the table; small pieces of Museum Putty™ were used to ensure that it did not "wander" during the tests. A lightweight vibration sensor (accelerometer) was attached to one of the arms of the object. The following tests were conducted:

1. Determination of the resonant frequency of the object: The object was subjected to vibrations continuously increasing from 1 to 100 Hz. The table was vibrated at the maximum allowable levels for each frequency according to the SBR guidelines. The object sensor measured the response of the object in terms of velocity as a function of frequency. Resonance occurred where there is a peak in velocity. For this object, several resonance frequencies were found, with the largest at approximately 50 Hz.

2. Fatigue test: In this experiment, the object was vibrated at the resonant frequency of 50 Hz at a level of 6 mm/s. This simulates the worst-case scenario, where the contractor produces the maximum allowable vibrations during the construction period with no damping for the exhibition. The object was first exposed to the resonant frequency for 30 minutes, followed by a 30 minute program of random frequency/velocity combinations from the SBR guideline. The object was then carefully examined by a conservator (second author of this paper) for damage. No visible damage to the object was found.

Figure 5
Deaccessioned sculpture mounted on a vibration table. Object provided courtesy of the artists, Heringa and Van Kalsbeek

3. Aesthetic test: During the fatigue testing, it was clear that the vibration of the loose arms of the objects was aesthetically disturbing. Given the indication that no visible damage would be expected during the construction work, the conservator was asked to determine what level of vibration would be aesthetically acceptable if the object were to resonate at 50 Hz. The vibration level was ramped up in both directions, that is, from 0 to 6 mm/s and back. The conservator indicated that a vibration level of 2.6 mm/s was acceptable in terms of movement of the arms of the object.

DESIGN AND SELECTION OF A DAMPING SYSTEM

Based on the results of the vibration analysis and testing, a damping system was designed to reduce the vibration level at 50 Hz from 6 mm/s to 2.6 mm/s. In other words, if the contractor stays within the SBR guidelines, the damping would ensure that the object would resonate at an aesthetically acceptable level.

Figure 6
Typical industrial spring used for the damping of the pedestals

Industrial (as opposed to consumer) grade springs supplied by Sebert were initially selected (see example in Figure 6). Each pedestal was fitted with several springs, the number and position depending on the weight and center of gravity of the combined object and pedestal.[2] The positioning of the springs made them virtually invisible, providing an aesthetically pleasing effect. The objects and pedestals appeared to "levitate" above the floor (see Figure 7). Vibration testing showed that the springs reduced the vibration levels at the top of the pedestals, that is, at the base of the objects, to the acceptable level of 2.6 mm/s.

Due to delivery problems, an alternate solution for damping had to be developed. For this solution, a foam rubber material produced by the Dutch company Innosel B.V. was used in strips under the pedestals.[2] The selected material, strip geometry and distribution of the strips under the pedestals also brought about the desired damping. It should be noted, however, that foam products are not generally recommended for long-term vibration damping since they permanently deform (are compressed) with time.

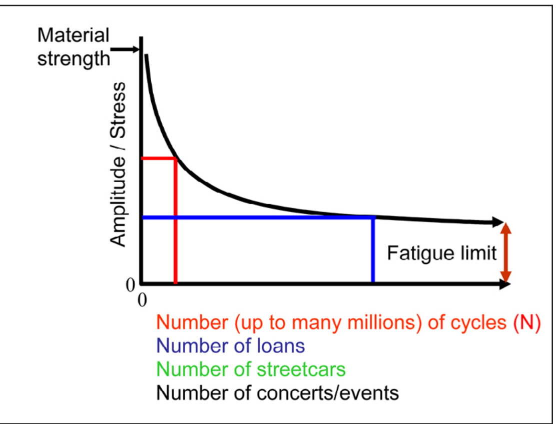

Figure 7
Example of pedestal mounted on springs

Figure 8
Schematic (S-N) fatigue diagram showing that at high vibration amplitudes, the number of cycles to failure (duration) is shorter (red rectangle) than at low amplitudes (blue rectangle)

DISCUSSION

The results of this project show that with proper knowledge of incoming vibrations, and the vibration limits for objects, solutions can be found to mitigate the effects of vibrations on sensitive objects, not only in museums near construction sites, but also in transport and other situations where vibrations may be a problem. This information provides a sounder basis for museums and contractors to find solutions for vibration problems suitable to all parties as shown schematically in Fig. 3b. In this case, contractors are still bound by local legislation limiting the production of vibrations. However, with some experimental work, museums will at least have an indication of what the vibration limits are for their collection, or for specific sensitive objects. They can use this information to select damping systems for their objects. On the other hand, with this information, contractors can also be asked to take reasonable actions to help lower the level of incoming vibrations.

The key problem which still remains is the almost complete lack of data relating vibration levels and dose to damage in objects. Vibration experiments such as those conducted during this project are critical to determining proper limits for vibrations. On a practical level, what are required are so-called S-N or Wöhler diagrams (see the schematic in Figure 8), which are well-known within the engineering world for determining the fatigue life of objects. These diagrams show how many cycles (N) an object can be exposed to at a given stress or deformation level (S) until it "fails". At high levels, the number of cycles to failure is lower than at low amplitudes. In this schematic diagram, which is common for metals, there is a lower limit of S below which no failure is expected. This can be a natural limit, or an artificially determined limit, such as the time between conservation treatments. The object may actually undergo "scheduled" treatment before fatigue "failure" would occur.

An S-N diagram like this can also be interpreted in terms of number of events. For example, in a pilot study, Wei et al. (2005) showed that loss of paint from several paintings in poor condition occurred after at least the equivalent of five rock concerts. Thus, the concept of the S-N diagram could also be used to determine how many vibration "events" an object may be exposed to. In other words, instead of just asking whether an object may be transported (once) or exposed to a (single) rock concert, a collection manager may also need to ask how many times an object can be loaned/transported, and/or exposed to a concert, or construction work. For the current example of the Stedelijk Museum, it was shown that damage would not be expected during the construction work discussed. However, the exposure would eventually contribute to damage if the objects were exposed to other vibrations in the future.

Clearly, it is not possible to create an S-N diagram for every single type of object and material. However, the concept of cumulative damage due to cyclic loading, including vibrations but also climate changes, should be recognized. Work at RCE is geared towards setting allowable levels and durations for given classes of objects.

POSTSCRIPT

The effectiveness of the system was shown on the vibration testing table. Unfortunately, as is customary with large construction projects, building work was delayed until after the exhibition was over, so that the damping system was not seriously tested in practice.

CONCLUSIONS

An integral approach was taken for the design of a damping system for sculptures exposed to construction work during an exhibition at the Stedelijk Museum Amsterdam. The design made use of Dutch building codes and vibration testing performed on real objects, and was a cooperative effort between the museum, the designer of the pedestals for the sculptures, a civil engineering consultant, a vibration testing facility and two manufacturers of damping solutions.

The results show that the proper protection of objects of cultural heritage is possible if there is reliable data both on the vibration levels which the objects will be exposed to and on their effect on those objects. Such an integral approach provides a better basis for cooperation between construction companies and collection managers. For the specific application, construction work would not be expected to lead to damage of the sculptures. However, they would cause aesthetically disturbing vibration of the objects. Two visually acceptable solutions using either industrial grade springs or foam rubber strips were found to dampen the pedestals upon which the objects were displayed to acceptable vibration levels.

ACKNOWLEDGEMENTS

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NOTES

[1] This statement is made for the sake of simplicity. Actually, materials under shock loading fail at a maximum amount of shock energy, which may be at a load different from the "static" material's strength (the stretching of a painting is an example of a "static" load (see Figure 2 a).

[2] The specific materials used for damping, as well as the specific details of the objects and testing are available from the principle author. They are not given here as they fall beyond the scope of this article, which focuses on the integral design methodology.

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