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EARTHQUAKE RESISTANT TELECOMMUNICATIONS STRUCTURAL SYSTEM

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ABSTRACT

A practical multi-discipline design method is presented for the seismic design of a large scale telecommunications structural system. The complete spectrum is reviewed from the early computer modeling and simulations to the manufacturing, seismic testing and installation of the system near active fault areas.

It is essential that telecommunications systems are fully functional after sustaining seismic shock activity. The design of a earthquake resistant electronic equipment structural system is addressed. The design techniques used allow the structural system to successfully protect the sensitive operating computers from strong seismic activity found in Zone 4 areas.

Computer modeling of the actual telecommunications system are addressed along with the finite element models and the structural elements. Dynamic nonlinear seismic analysis of the telecommunications finite element model are presented. Laboratory triaxial simulation tests of the operating telecommunications system are shown and reviewed. The excellent correlation between the analytical seismic analysis of the finite element models and the laboratory seismic tests of the actual system are discussed. Conclusions and recommendations of this work are included.

KEYWORDS

Earthquake resistant; structure; telecommunications; disk drive; finite element; normal modes; dynamic analysis; seismic simulation; Zone 4; patent.

INTRODUCTION

It is desirable to protect electronic equipment from damage during earthquake or seismic shock activity. In particular, it is an essential requirement that after an earthquake or seismic shock, telecommunications equipment located in the earthquake vicinity is operational. In addition, it is desirable that the telecommunications equipment located in the earthquake area is operational during the actual earthquake or seismic shock. With this objective in mind, telecommunications equipment has been mounted in specially designed frames which are intended to support the equipment in such a manner that it is able to withstand the most severe earthquakes and seismic shocks which are likely to occur in that vicinity. It is known that an earthquake resistant frame should have as high a natural vibrational frequency as possible. To make such frames rigid for this purpose, they are normally made of massive section structures with large section bracing and stiffening members. A major problem inherent in such technological thought is that the frame is extremely heavy and expensive to manufacture. A further problem found, is that conventional frames have methods of securing them to underlying supporting structures, such that the frames are incapable of satisfactorily protecting the equipment from severe damage caused by earthquake activity for all supporting methods employed. For instance, one conventional frame when mounted securely upon a concrete floor, has a natural vibrational frequency of approximately 6.5 Hz. This frequency is acceptable to prevent damage to telecommunications equipment held by the frame when subjected to an earthquake measured with an intensity of about 8.3 on the Richter scale. However, for various reasons it is sometimes normal for telecommunications equipment to be housed upon upper stories of buildings, e.g. the second or third story. The horizontal acceleration levels in movements of floors during seismic activity increases from floor-to-floor upwardly from the ground. It follows that when conventional frames are mounted upon an above ground floor there is the problem that the acceleration levels of movement of the floor effectively acts upon the frame so that it is less likely to protect telecommunications equipment from strong earthquakes or seismic activity.

Further, in a room housing telecommunications equipment, it is normal practice to provide a false floor above the structural floor of the building to form a space beneath the false floor to accommodate electrical wiring and air circulatory equipment used with the telecommunications equipment. Such false floors are designed to have only sufficient strength to safely support the weight of operators and the telecommunications and ancillary equipment. However, the horizontal natural frequency of these false floors are too low to make them suitable to carry the weight of the telecommunications equipment and its supporting frames. As a consequence, the telecommunications equipment and supporting frames need to be carried by the structural floor and to enable this to be done the telecommunications equipment and frame extend upwardly from the structural floor through an aperture in the false floor. The aperture is necessarily spaced laterally from the telecommunications equipment and frame to enable personnel to move close to the lower end of the equipment which necessarily is disposed downwardly of the support surface of the false floor and for this purpose steps must be provided down through the aperture to the structural floor. This results in complex structure which would be unnecessary if the frame could be raised to at least the level of the false floor whereby the lower parts of the equipment would be accessible to personnel standing upon the false floor. However, to permit this to occur the frame must be supported upon a pedestal from the structural floor. The pedestal itself has its own natural frequency which in combination with the conventional frame mounted above it, produces a lower natural frequency for this combination than the frame itself. Unfortunately, this natural frequency is so low that equipment carried thereby would not be satisfactorily protected against strong earthquakes.

DESCRIPTION of STRUCTURAL SYSTEM

The structural system seeks to provide an earthquake resistant electronic equipment frame which in use will minimize the above problems.

The electronic equipment support frame is comprised of a plurality of column members and frame base members extending between the column members. This holds the upwardly extending frame members in fixed relative positions. Base members have regions extending directly from the upwardly extended frame members and are more massive construction than other parts of the base means which are more remote from the upwardly extended frame members. The more massive regions being rigidly secured to the upwardly extending members are formed with apertures for receiving screw-threaded members to mount the frame upon a support.

When the frame is secured to an underlaying support the stiffness of the frame is partly dependent upon first the massive construction of the more massive regions at the base means secondly the rigidity of the structure between the massive regions and the upwardly extended frame members and thirdly upon the location of the apertures relative to the upwardly extending frame members. These apertures should be disposed as close as is practical to the upwardly extending frame members. The close positioning dependent upon the type of screw-threaded securing members which are located through the apertures to mount the frame upon the support and their accessibility needs. In an ideal situation it is envisaged that the position of the apertures should be no greater than 1.50 inches (3.81 cm) away from the upwardly extending frame members. Hence, with a structure of the support frame described, the positions of the apertures affect the stiffness of the frame upon the support. Stiffness increases with decreasing distance of the apertures from the upwardly extending frame members. The massive regions of the base means ensure that insignificant bending takes place in the structure between the apertures and the upwardly extending frame members so that stiffness is maximized in these regions. In frame structures of this type when using frame members and base means made from steel box frame structures, a frame weight of approximately 128 lbs (58.1 kg) is achievable to provide a natural vibrational frequency of 13 to 14 Hz with the frame securely mounted upon a concrete floor. This vibrational frequency is suitable for protecting equipment when mounted upon an upper storey, i.e. upon a structural floor, and in addition, when mounted upon pedestals. More particularly, the box frame structure employed in conjunction with an adjustable height pedestal having a natural vibrational frequency of 70 to 80 Hz, an acceptable natural vibrational frequency of at least 7.4 Hz for the combination of frame and pedestal is obtainable.

In a preferred arrangement, the upwardly extending frame members are formed from carbon steel tubing which is of box-type construction in cross-section. With such an arrangement, the more massive regions of the base means are preferably secured to the upwardly extending frame members by a welding operation to provide the necessary rigidity. In addition, it is preferable to have the more massive regions rigidly secured to the remainder of the base means by welding.

Preferably, the upwardly extended frame members are at their lower ends disposed at corners of a polygon. Some of the massive regions of the base lie along the sides of the polygon. With this preferred arrangement, the apertures in these more massive base regions may be disposed outwardly from electronic equipment to be mounted within the frame so as to be accessible for mounting and disconnecting the frame from a support. With such an arrangement, it renders it possible to assemble the frame and locate the equipment within it before the frame is moved to its operational position for securement purposes. This procedure may be more convenient than first requiring the frame to be located in its operational position followed by assembly of the equipment into the frame.

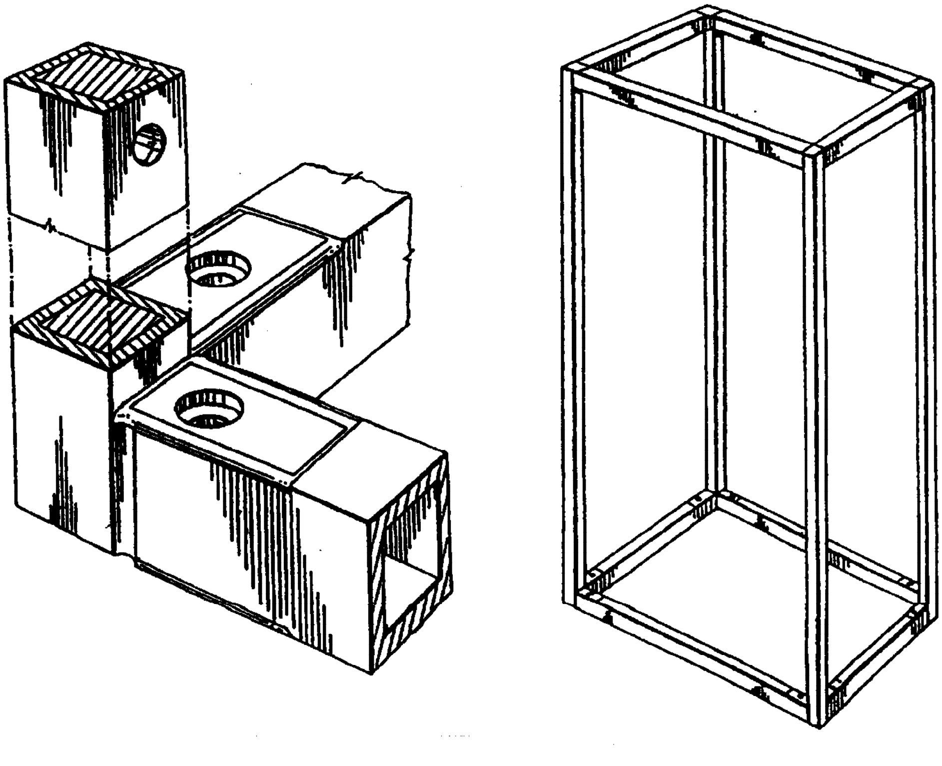

FIG. 1. Trimetric view of an earthquake resistant structural support frame.

Embodiment of the telecommunications structural system will now be described by way of example, with reference to the accompanying drawings, in which: FIG. 1 is an trimetric view of an earthquake resistant support frame along with the additional exploded view of the corner (Meyer, 1995).

As shown in FIG. 1, the earthquake resistant structural support frame comprises four vertically extended frame members which are located at the four corners of a rectangle in plan view. The four members being secured at their upper ends by rigid horizontal members extending along edges of the rectangle. Frame members are made of carbon steel tubing of rectangular or square cross-section. Vertical frame members are 1.5 inches (3.81 cm) square with a thickness of 0.12 inches (3.05 cm) and a height of approximately 76 inches (193.04 cm).

At their lower ends, the frame columns are secured in relatively fixed position at the corners of the rectangle by a frame base means. The base means comprises four base frame members each of which in turn comprises an elongated intermediate element extending along a side of the rectangle between successive frame members. Intermediate elements are rectangular box sections with greater height than width for maximum strength and to advantageously increase the natural frequency of the structure. To achieve these requirements, each element has a height of 2 inches (5.08 cm) and a width of 1.5 inches (3.81 cm). The elements extend to the associated column members. End regions of the base frame members are more massive to increase the rigidity and stiffness of the total structure. As is shown by the exploded view, at the more massive end regions of the base means are provided end members which are of block structure carbon steel material of rectangular cross-section so as to fit snuggly between vertical opposing sides of the respective elements. The upper and lower sides at the end regions of each of the elements are removed, as shown in the exploded view. This is to provide a slot into which an end member is snuggly received in contact with the inside faces of the sides of the elongated elements.

The end members have a depth sufficient to extend outwardly in both vertical directions to lie coplanar with the outside surfaces of the upper and lower sides of the elements. The end members are welded into position into the slots by weld fillets between the sides and the end members and weld fillets between the inner ends of the end members and the ends of the sides forming the bases of the slots. The end members and the elongated intermediate elements are thus rigidly secured together. The end members and the base elements are also rigidly secured to the vertically extending column members also by welding. As is particularly shown in FIG. 1, the ends of the sides are chamfered, this chamfer extending into the ends of the end members. A weld fillet is provided between the vertically extending frame members on the one hand and the sides and the end members on the other hand, this filet being provided in the space formed by the chamfer. As may be seen, this results in each end member being welded to its respective vertically extending frame member in addition to the sides of the elongated elements being secured to the frame member. A weld line is also provided along the top and bottom outer end of each member to rigidly secure it to its respective vertically extending member.

Each of the end members is formed with a vertically extended through aperture for receiving screw threaded members to mount the frame upon a support. As may be seen from the above description, when a bolt is positioned through each of the apertures for holding a frame in position on supports the support load is taken both through the associated end members and the sides of the elongated element into the adjacent column member. Because of the ridged connection between the end members and the elongated elements with the column frame members, the rigidity of the frame is maximized with negligible bending being permitted between each aperture and the adjacent column member.

To assist in the stiffness when two or more of the frames are being assembled side-by-side, each of the vertically extending frame members is provided at its lower and upper ends with block carbon steel inserts (FIG. 1) which extends to the lower and upper ends of the frame and are welded in position. Two horizontally extending apertures are formed through each of the column members so as to pass through the insert, one aperture towards the lower end of each member (FIG. 1), and one towards the top (not shown). These apertures are aligned with each other from frame-to-frame when the frames are assembled side-by-side for passing securing bolts through them so as to secure the adjacent frames together and increase the total stiffness.

FINITE ELEMENT METHOD AND SEISMIC SIMULATION

Embodiment of the structural system particularly when the frame is loaded with telecommunications equipment will now be described by way of finite element models and seismic simulation, with reference to the accompanying representation, in which: FIG. 2 is a trimetric view of the floor mounted finite element model and with telecommunications equipment staged on the seismic simulator; FIG. 3 is a trimetric view of pedestal mounted finite element model and pedestal mounted telecommunication equipment staged on the seismic simulator.

FIG. 2. Finite element model and telecommunication equipment staged on seismic simulator.

As shown in FIG. 2, the finite element model is exact mathematically to the telecommunication equipment physical size and weight, e.g. 75.91 inch height, 24 inch width, 36 inch depth (192.81 cm, 60.96 cm, and 91.44 cm) and 970 lbs (440 kg) weight. It is grouped with 548 active carbon steel (C 1020) quadrilateral shell elements with thickness of 0.120 inch (0.3048 cm). It is secured to the mounting surface at the apertures near the vertical extending columns. Nodes at these locations have zero degrees of freedom, e.g. translation and rotation about x-axis, y-axis, and z-axis is zero. Telecommunications equipment is positioned on a reinforced concrete slab (fixed to the triaxial seismic simulator) with M12 Hilti anchors. Simulator is located at Wyle Laboratories, Inc. in Huntsville, Alabama (U.S.A.).

The frame described in this embodiment performs satisfactory when mounted in different locations to protect telecommunications equipment contained therein from high intensity earthquake activity. For instance, as shown by FIG. 3, the frame is particularly useful when mounted upon a pedestal which is supported upon a structural floor of a building. With this, a computer room false floor is disposed above the floor, the false floor being provided for holding the weight of operators, maintenance personnel and equipment and forming a space beneath the false floor for passage of air conditioning cooling air and electrical cables. The pedestal is of known construction and is adjustable, e.g. between 21 and 28 inches (53.34 and 71.12 cm) in height.

This pedestal is disposed upon the upper surface of the structural floor and extends upwardly into an aperture formed in the false floor so as to hold the frame and contained electronic equipment above the aperture. Thus, the lower regions of the equipment are completely accessible by personnel standing upon the false floor.

The frame may be easily secured to the pedestal by the use of a solid metal plate which is bolted onto the upper surface of the pedestal. This plate extends outwardly slightly beyond the edges of the pedestal whereby the base frame members may be disposed upon the plate and slightly outwardly from the frame of the pedestal. This enables bolts to be positioned through the end members to be secured in position beneath the plate by nuts.

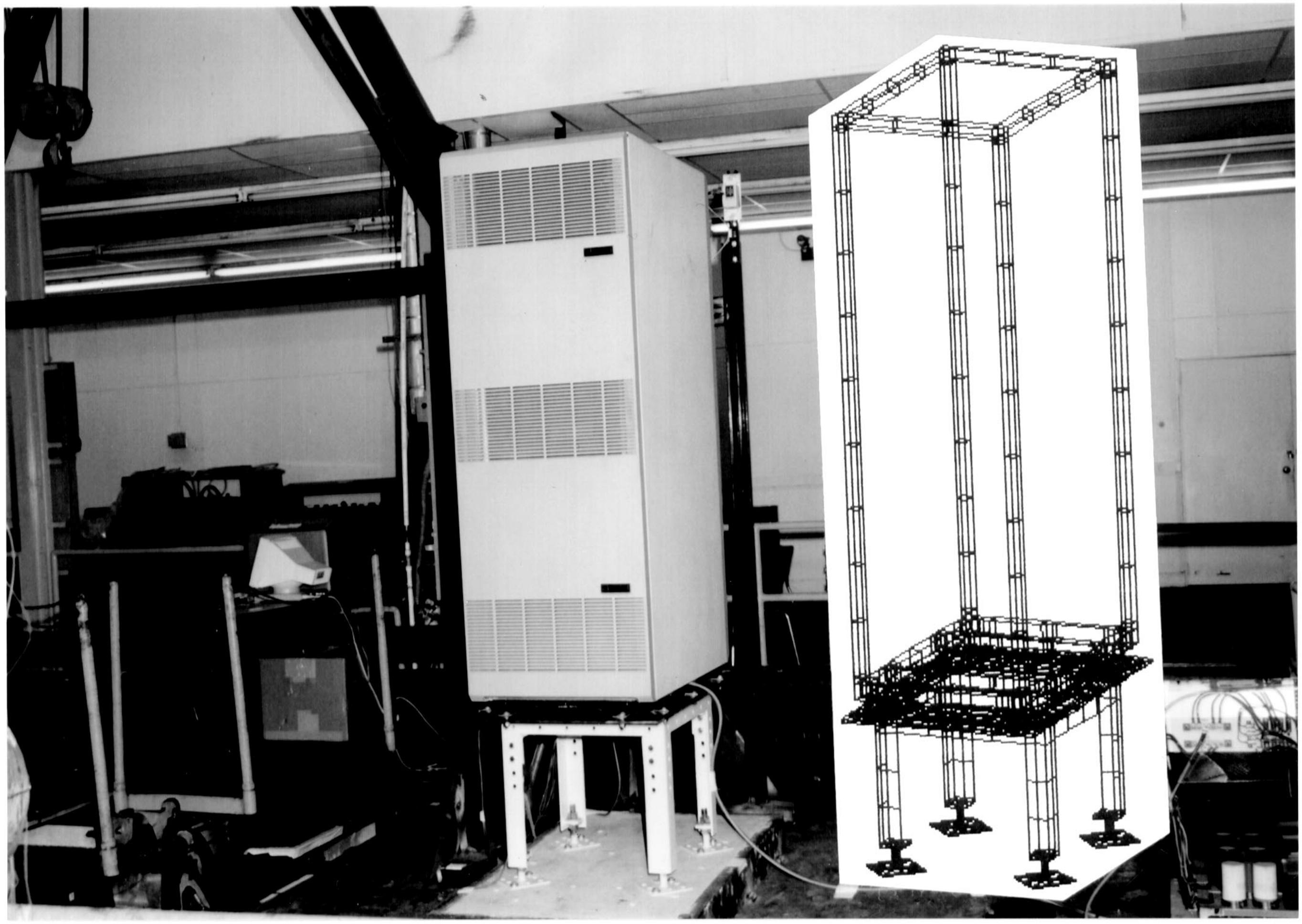

FIG. 3. Pedestal mounted finite element model and telecommunications equipment on seismic simulator.

As shown by FIG. 3, the finite element model is exact mathematically to the pedestal mounted telecommunications equipment physical size and weight, e.g. 99.55 inch height, 24 inch width, 36 inch depth (252.85 cm, 60.96 cm, and 94.44 cm) and 1,168 lbs (530 kg) weight. It is grouped with 1,176 active carbon steel (C 1020) elements, consisting of 752 quadrilateral shell elements, 264 hexahedral (brick) elements, and 160 pentahedral (prism) elements. The model is secured to the mounting surface at the square mounting plates of the pedestal. Nodes at these locations have zero degrees of freedom, e.g. translation and rotation about x-axis, y-axis, and z-axis is zero. Telecommunications equipment and pedestal are staged on a reinforced concrete slab (fixed to the triaxial seismic simulator) with M12 Hilti anchors.

Finite Element Analysis and Seismic Simulation at Wyle Laboratories

Finite element representation of the embodiments of the telecommunications structural system are analyzed in two steps, e.g. normal modes and transient response. Software utilized is CDA/sprint of Houston, Texas.

Table 1., presents the comparison between modal analysis and resonant frequency search completed by Wyle Laboratories. Normal mode shapes and natural frequencies define the natural free resonant vibration behavior of the system. Natural frequency associated with each mode defines the frequency at which this resonance will develop. Only the low frequency shapes are necessary for dynamic studies of practical interest. It is an inherent feature of finite element method that the low frequency mode shapes are computed and furthermore, that the highest accuracy is obtained for the lowest frequencies (CDA/sprint, 1994). This property blends well with requirements for forced time and frequency response of the telecommunications equipment. Jacobi and subspace iteration are the methods used for these models. As the name implies, subspace iteration is an iterative method. Trial vectors are created and iterated until eigenvalues (natural frequencies) converge to a preset tolerance. The solution proceeds until eigenvalue convergence or the number of allowed iterations is exceeded. The Jacobi method of eigenvalue extraction is slower, though more stable, than the subspace iteration method.

Table 1. Synopsis of Modal Analysis (Subspace Iteration) and Wyle Laboratories Tests

Model	Resonant Frequencies Hz		
	X-Axis (Side-Side)	Y-Axis (Top-Bottom)	Z-Axis (Front-Back)
Floor Mounted FEM Frame	13.4 Hz	19.7 Hz (Twisting)	13.2 Hz
Floor Mounted Telecommunications	13.3 Hz	19.0 Hz (Twisting)	19.0 Hz
Pedestal Mounted FEM Frame	11.4 Hz	18.7 Hz (Twisting)	11.7 Hz
Pedestal Mounted Telecommunications	7.4 Hz	18.7 Hz (Twisting)	8.4 Hz

As shown by Table 1., significant correlation exists between analytical calculated frequencies and the actual measured resonant frequencies. Frequencies for both finite element model frame and the finite element model of the pedestal mounted frame are shown for the unloaded structure. High frame stiffness is apparent. The z-axis (Front-Back) stiffness is further increased in the actual telecommunications equipment by the addition of side panels.

Dynamic solutions of the finite element models require reductions in the size or number of degrees-of-freedom of the mathematical model. The Guyan reduction technique or static condensation is used to achieve this objective (Zienkiewicz, 1977 and Cook, 1981). Process involves selecting displacement components for which the stiffness forces are much greater than the damping and inertial forces and which have no external forcing input. These components are eliminated from the model using static solution procedures. Remaining model in terms of smaller set of components is then solved. Static components of displacement are not lost in the solution nor are they set equal to zero. The values are determined statically and these static values are combined with the dynamic components to compute the total system response. Dynamic components are referred to as active or master components.

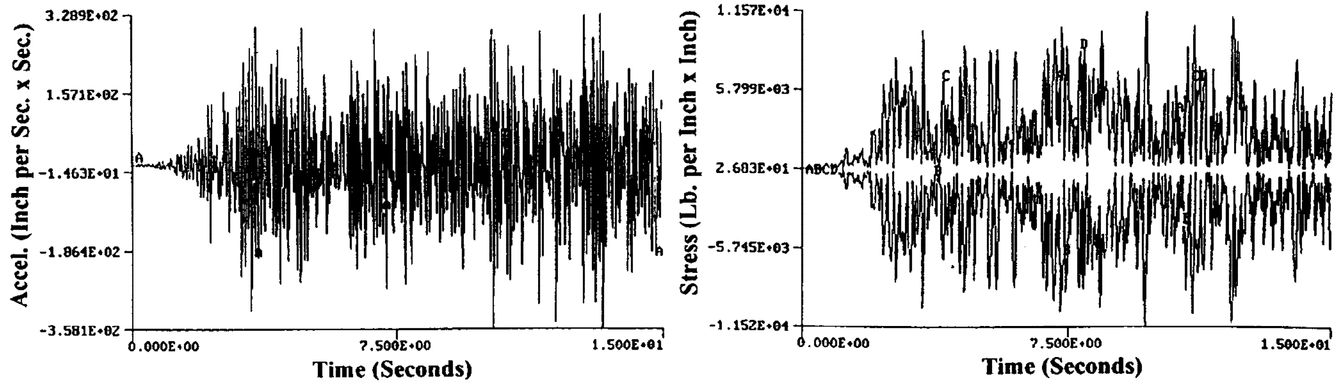

FIG. 4. Typical acceleration and stress time-histories for finite element models

Embodiment of the telecommunications structural system will now be described by results of dynamic finite element analysis and earthquake simulation, with reference to the accompanying graphs and table, in which: FIG. 4 indicates typical dynamic time-history analysis; and Table 2 arrays typical seismic simulation spectral information.

Figure 4, shows a typical acceleration time-history of the seismic calculation near the mounting point of the sensitive disc drives within telecommunications equipment and a typical stress time-history of the calculated stress values for a given element within the finite element model. The component and element time-histories are shown shortened to about 15 seconds, since maximum values develop within this time period. Disk drive acceleration levels of 0.9 g are within acceptable manufactures operating levels. Maximum stress levels of 11,530 lbs / square inch (7.9493 x E 08 dynes/ square centimeter) are acceptable. Stress time-history shown contains the major, minor, shear and Von Mises stress levels.

Table 2, arrays prevalent simulated side-to-side (x-axis) earthquake spectral data measured on operating telecommunications equipment, while mounted on the seismic simulator. Equipment is subjected to Zone 4 test in each axis for both mounting configurations. Typical data analyzed by a response spectrum analyzer at 2% damping over a frequency range of 200 Hz. System is fully functional, including disk drives, before, during and after the seismic simulation.

Table 2. Simulated earthquake spectral data on operating telecommunications equipment

Acceleration Level 2% Damping	Frequency (Hz.)									
	4 Hz.	5 Hz.	6.3 Hz.	8 Hz.	9 Hz.	10 Hz.	12.5 Hz.	14 Hz.	16 Hz.	20 Hz.
Input Floor Mount	5.6 g	5.5 g	4.3 g	3.5 g	3.3 g	3.4 g	3.3 g	2.8 g	2.8 g	3.1 g
Floor System *	6.5 g	6.6 g	5.8 g	6.2 g	6.7 g	9.4 g	9.4 g	4.8 g	3.9 g	3.0 g
Floor System **	6.0 g	6.5 g	5.5 g	6.2 g	7.5 g	9.2 g	10.0 g	6.0 g	3.9 g	3.8 g
Input Pedestal Mount	6.0 g	5.5 g	4.1 g	3.8 g	3.4 g	3.5 g	3.6 g	2.9 g	2.7 g	2.9 g
Pedestal System *	12.1 g	20.0 g	39.0 g	12.0 g	9.2 g	8.0 g	7.7 g	6.1 g	9.0 g	7.4 g

*Disk Drive Mounting Area ** Triaxal Simulation

CONCLUSION

The earthquake resistant telecommunications structural system provides significant protection that even sensitive operating disk drives within the operating equipment are not disturbed by seismic shock activity. Finite element analysis accurately predicted system performance for both the structure and sensitive components. Seismic simulation verified both the design and the finite element analysis. Telecommunications equipment of this form are functioning in various Zone 4 seismic locations.

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