USE OF VISCOS DAMPERS AND SHOCK TRANSMISSION UNITS IN THE SEISMIC PROTECTION OF BUILDINGS

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SUMMARY

Both Fluid Viscous Dampers (FVDs) and Shock Transmission Units (STUs) are piston/cylinder devices providing velocity dependent behavior, albeit characterized by very different constitutive laws. These technologies have been in use for more than 20 years to improve the seismic behavior of bridges through energy dissipation (i.e.: dampers) or additional dynamic restraints (i.e.: STU utilization).

Building applications are much less frequent and mostly limited to steel structures - usually aimed at reducing motion due to wind-storms or, when combined with isolators, at increasing the energy dissipation capacity of seismic isolation systems.

However, owing to the availability of highly reliable and relatively low cost devices on the market, new applications have recently been implemented in reinforced concrete buildings, both new and retrofitted. For instance, STUs have been used when existing expansion joint gaps between adjacent buildings are not large enough to avoid pounding. Applications in monumental masonry buildings have also been implemented.

This paper describes some recent projects like the Marin County Civic Center in California-USA, the “Dives in Misericordia” Church in Rome (Italy), The Emilia-Romagna Tower in Bologna (Italy), the Santa Maria della Misericordia Hospital in Udine (Italy) and the Basilica of San Francesco in Assisi (Italy). Qualifications and acceptance tests on the units are also reported.

INTRODUCTION

Fluid Viscous Dampers (FVDs) and Shock Transmission Units (STUs) have been in use in bridges and viaducts for more than 20 years. In Italy, for example, the first applications of STUs and FVDs took place in 1977 and 1984, respectively. Since then, said devices have been continuously developed, and applied in
hundreds of bridges all over the world. Recent STU and FVD outstanding applications are the Storaebelt Bridge in Denmark (Infanti [1]) and the Rion Antirion Bridge in Greece (Infanti [2]), respectively.

STUs are usually adopted to change the bridge structural system from isostatic under service loads to hyperstatic under dynamic loads (generally earthquakes, but wind sometimes too), so the advantages yielded by the two concepts can be maintained. FVDs are used as components of bridge seismic isolation systems to reduce seismic forces on piers and foundations and, at the same time, significantly reduce displacements.

The advantages accrued by using these technologies have recently become well-known even to the design engineers of buildings and, consequently, the applications of both STUs and FVDs in buildings continue to increase. This paper describes these technologies as well as the applications thereof.

**FLUID VISCOUS DEVICES: DAMPERS AND SHOCK TRANSMISSION UNITS**

Fluid viscous devices are piston/cylinder devices that utilize fluid flow through orifices to provide a reaction that is a function of the velocity applied to the aforesaid piston. The orifices are located in the piston head and this allows the fluid to move back and forth between two chambers. The cylinder is filled with a silicon fluid selected for its rheological stability and its being non-corrosive. The force generated by these devices is the result of a pressure differential across the piston head. These devices are equipped with spherical hinges at both ends to keep the transmitted load aligned along the main axis. This detail is of major importance to yield reliable performance: it prevents the piston rod from bending and thus the sealing system from failing. High-strength steel components are used for the vessel and the plated piston rod so as to withstand the actions imposed by dynamic loads. The anchoring details depend only on the structure to which they are anchored: for example, the tang plate/clevis system illustrated in Figure 1.

![Figure 1 - Typical anchoring configuration of a fluid viscous device (photo taken during the installation).](image)

A very important issue related to the utilization of the technology entails the correct numerical modeling of the devices as integrated into the structural model.
The most appropriate mathematical model to represent the behavior of viscous devices is to use a Maxwell constitutive law characterized by a linear spring in series to a non-linear dashpot element (see Figure 2). The first element represents the elasticity of the device; the second, its damping properties. Device elasticity, represented by the stiffness \( K \), is mainly due to the compressibility of the fluid, whilst the damping parameters \( C \) and \( \alpha \) depend upon the hydraulic circuit used with the particular unit. Thus, the reaction force to a displacement \( x \) applied with a velocity \( \dot{x} \) is given by:

\[
F = C \left( \frac{\dot{x}}{K} \right)^\alpha
\]

In other words, the main difference between an STU and an FVD resides in the relative importance given to the two aforesaid components of the total behaviour: the stiffness and the damping. In fact, whilst an STU, by definition, needs to provide a very stiff reaction in order to reduce as much as possible the relative dynamic movements between its two ends, an FVD is designed to dissipate energy and thus allow relatively large movements between its two ends.

In this manner, it is clear that the dashpot characteristics of the Maxwell model are important in an STU only because they already activate a very stiff spring at low velocities. This is why STUs are presently modeled as very stiff springs only. The stiffness \( K \) can be approximated with the nominal force of the device divided by 5% of the stroke (the latter depends on the thermal displacement that shall be guaranteed).

Conversely, viscous dampers are commonly modeled using a non-linear dashpot element only, because the energy elastically stored into the device during the dynamic event is negligible most of the time as compared to the energy dissipation. In other words - as a rule of thumb - a viscous damper can be simply modeled by a dashpot element when the maximum expected stroke is at least 10 times the elastic deflection of the spring element.

The exponent that characterizes the non-linearity of the damper response as a function of the velocity is of prime importance. Positive effects are undoubtedly related to low exponent dampers: e.g., reduced pier deformations, lower expansion joint costs and cost effective bearings in bridge applications or, in buildings, a maximal reduction of relative displacement at the isolation interface or in the braces. FIP viscous dampers are designed to guarantee a 0.15 exponent so reaction can be expected to be almost constant within a wide velocity range. This performance characteristic permits the devices to initiate their damping reaction at low velocities, providing a maximal reduction of structure displacements. Total system elasticity, mathematically represented by the stiffness \( K \), is particularly evident at the point of motion reversal, or at any rate, at the point of transitory phases. Commonly, it is a secondary effect and, as mentioned above, it is often not even computed. Observing the plot in Figure 3, it can be noted that the typical hysteresis loop of a FIP FVD looks almost rectangular even though the displacement time-history is sinusoidal (thus velocity-dependent). This is due to the damper characteristic exponent, that is very low (\( \alpha = 0.15 \)), and makes the behavior almost independent from velocity. Thus, total damper behavior is similar to that of a spring in series with a ”perfectly plastic” element characterized by a constant threshold force.
Another important issue related to the use of fluid viscous devices is the performance verification of the finished product through testing. In the last few years, FIP viscous dampers have undergone major qualification testing programs at the FIP laboratory as well as at other independent facilities (Earthquake Engineering Research Center, Berkeley CA – USA, Boeing Testing Facility, Canoga Park CA – USA and Caltrans SRMD Testing Laboratory at the University of California – San Diego – USA; see Infanti [2], [3], and [4]). This entitled the company to be a pre-qualified damper manufacturer for the Golden Gate Bridge Retrofit project as well as to enter the CALTRANS (California Department of Transportation) list of pre-qualified damper manufacturers. It should be noted that remarkable reaction stability has been achieved by dynamically cycling within a very wide temperature range (-40°C ÷ +50°C) which guarantees proper behavior under any type of environmental conditions. Some examples of acceptance tests on both FVDs and STUs are described in the following paragraphs.

**EXAMPLE OF FLUID VISCOUS DAMPERS USE**

A recent example of the use of fluid viscous dampers in a building for its seismic protection is reported in the following paragraph. It is worth noting that FVDs can also be used for wind protection in buildings. As an example, the Tapei Financial Center (a high rise building in Taipei, Taiwan, see Reina [5]), protected from windstorms through a tuned mass damper on the roof (in which damping is provided by fluid viscous dampers with particular characteristics manufactured by FIP Industriale).

**The “Dives in Misericordia” Church, Roma, Italy**

The “Dives in Misericordia” Church, that owes its name to an encyclical of Pope John Paul II, was built as a symbol of the Year 2000 Jubilee in a peripheral district (Tor Tre Teste) of Rome. It was designed by architect Richard Meier, the winner of an international competition. The design is characterised by three large parallel white pre-cast concrete sails – creating the central nave - which swell as though driven by a wind from the east (Figure 4). The height of the three sails is respectively 16.8 m, 22.1 m and 26.7 m. Though the city of Rome was not classified as seismic by the Italian seismic code at the time the design was conceived, and due to the importance of the structure, its design was revised in order to allow it to withstand an earthquake with a PGA=0.11 g, defined by a site-specific seismic hazard study (Dalmagioni [6]). The analyses showed that the biggest problems induced by an earthquake would be the seismic displacement of the highest sail – that should have been lower than 10 mm to avoid damage to the large glass surfaces connected to the sails – as well as the stresses at the base of the highest sail. To reduce both displacements and stresses, it was decided to connect the sail to the steel beams of the glass roof through fluid viscous dampers. This solution gave the structure satisfactory seismic behaviour without any major
change to the general structural design based on service loads (static loads and wind), except for small changes in secondary structural elements [6].

The viscous dampers selected were highly non linear, as those described above and thus, endowed with the highest energy dissipation efficiency. Thirty-two dampers were installed, two per beam, in order to keep the force transmitted by the dampers in axis with the beam (Figure 5). Each damper has a design force of 4.5 kN and a force vs. velocity constitutive law $F = 2.25 \cdot V^{0.14}$ where the force $F$ is in kN and the velocity $V$ in mm/s.

A specific requirement was to have virtually maintenance-free devices. Thus, the structural components of the devices are all made of stainless steel. It is worth noting that the devices have spherical hinges at their ends (Figure 6).

A series of tests was carried out to check the behaviour of the devices. Cyclic tests at constant velocity were carried out at the laboratory of FIP Industriale (Figure 7), at 6 different velocities in the order of 12.5% to 200% of the design velocity (150 mm/s). The results of these tests are shown in Figure 8, in comparison to the theoretical force vs. velocity curve. All the experimental data were within the acceptance range ($\pm 15\%$ of the theoretical force), even outside the design velocity range. A sinusoidal test at a frequency of about 0.5 Hz (corresponding to a maximum velocity of 150 mm/s, i.e. the design velocity) was also carried out to check whether the dissipated energy per cycle was higher or equal to 85% of the theoretical dissipated energy. The measured value was practically the same as the theoretical value.

![Figure 4 - The “Dives in Misericordia” Church.](image_url)
Figure 5 - Viscous dampers installed in the “Dives in Misericordia” Church.

Figure 6 - Viscous damper for the “Dives in Misericordia” Church (dimensions are in mm).

Figure 7 - A viscous damper under testing at FIP laboratory.
EXAMPLES OF SHOCK TRANSMISSION UNITS USE

The use of STUs that act as temporary restraints only during dynamic actions, is quite common in bridges and viaducts, and more recently, in buildings as well. In the latter, STUs are often applied in pre-cast structures – to provide a dynamic connection of different structural elements without inducing constraint stress due to thermal changes - or to connect large roofs (e.g. in stadiums) to their support structures. Some examples of this type of STU application in Italy are: the indoor Folgaria stadium, an ice-skating rink in Cortina, the Nola Interporto roofing, the industrial Pirelli buildings in Battipaglia as well as ST Microelectronics in Catania, the Bologna airport parking, the Esselunga Shopping Center in Arezzo. Conversely, particularly in retrofits, STUs are sometimes used instead to connect adjacent buildings (for example, to avoid pounding when the seismic gaps are not sufficiently large). The latter happens when said gaps were designed taking only into account thermal displacements because the area in question was not classified as seismic at the time of construction.

The Marin County Civic Center Hall of Justice, California, USA

The Marin County Civic Center, located in San Rafael, approximately 20 miles north of San Francisco, was one of the last buildings designed by architect Frank Lloyd Wright (Figure 9). It was built in 1957, to house various public offices. A portion of this building, the Hall of Justice, has recently undergone a seismic retrofit intervention based on the use of dissipative braces and STUs. Said STUs were used at expansion joints locations to connect the different portions of the building during an earthquake, and yet allow slow movements due to thermal expansion or other service loads without significant reaction (Figure 10). In total, 29 STUs were installed, with a design force in the order of 450 kN to 2000 kN and design displacements of ±75 mm.
All devices were subjected to acceptance tests carried out at the FIP Industriale laboratory (Figure 11). The devices were tested in their fully assembled configuration including hinges. The following tests were carried out: 1) shell proof pressure test; 2) full cycle stroke test; 3) performance test. Actually, the performance test was initially required for only 20% of the devices. Nonetheless, due to the importance of the building, it was carried out on all the units.

The shell proof test was conducted by pressurizing the STU with its fluid at a pressure equal to 125% of the maximum normal service pressure (about 300 bar) for a minimum of 3 minutes, and by checking that there was no fluid leakage during or after the test. There were no leaks detected in any of the devices, even though some of the devices were subjected to a pressure higher than that required.
The full cycle load test comprised the application of two full sinusoidal cycles with an amplitude of ± 57 mm (2 ¼ in) at a frequency of about 0.0011 Hz, equivalent to a peak velocity of 0.40 mm/s with a mean velocity of 0.25 mm/s. Test results were considered satisfactory because neither signs of structural binding nor identifiable leaks were observed during a post-test inspection. Figure 12 shows a force vs displacement graph obtained in one of said tests.

![Figure 11 – A 450 kN STU for the Marin County Civic Center undergoing test.](image)

![Figure 12 – Force vs displacement graph obtained in a full cycle stroke test on a 900 kN capacity STU.](image)
The aim of the performance test was to check for “lock-ups” and bleed rates. It actually consisted of two types of tests. A “Sinusoidal Activation test” is aimed at checking whether the device reacts to the maximum load (i.e. “lock-ups”) at velocities not greater than those required (2.5 mm/s ≅ 0.1 in/s). It was carried out by imposing sinusoidal movements with an amplitude of ±15 mm at a frequency corresponding to a peak velocity lower than 2.5 mm/s (in the range 1.2÷1.8 mm/s) and checking whether the load was higher than the design load. The second performance test was the “bleed rate” test, conducted by applying a load at a velocity of circa 5 mm/s (≅ 0.2 in/s), higher than the “lock-up” velocity, and, as it reaches the design value, by maintaining it constant for a few seconds. The bleed rate was measured during the latter phase and resulted almost equal in the two directions of movement, in the order of 0.91 to 1.58 mm/s.

The Emilia-Romagna Tower, Bologna, Italy

The Emilia-Romagna Tower is under construction in Bologna as the new headquarters of the offices of the Emilia-Romagna Region. As shown in the scheme in Figure 13, STUs are used in this case to couple the lower buildings to the tower and reduce the forces and displacements governing the dynamics of the tall tower structure, without adding any restraint to the mutual displacements generated by temperature changes and concrete creep and shrinkage (see Giuliani [7]).

A total of 12 STUs will be installed during the Spring 2004, with a design force of 700 kN and design displacements of ± 40 mm. Acceptance tests will also be carried out with one device. Figures 14 and 15 show how the devices are installed in the structure.

Figure 13 – Emilia Romagna Tower buildings coupled through STUs (courtesy of G.C.Giuliani, Redesco srl).
The Santa Maria della Misericordia Hospital in Udine, Italy

The Santa Maria della Misericordia Hospital in Udine, in north-eastern Italy, is a new structure presently under construction. It is U-shaped in plan and comprises three buildings. Most of the structural elements are pre-cast. A total of 39 STUs, with a design force of 250 kN and design displacements of $\pm 25$ mm, are installed at each floor, in the expansion joints between the buildings. In this case, the use of STUs in the
joints between the buildings permits keeping joint gaps much lower than it would be needed to allow thermal displacements as well as seismic displacement and, of course, to avoid pounding.

The Basilica of San Francesco in Assisi, Italy

The Basilica of San Francesco in Assisi, Italy, built in the 13th Century, was severely damaged by the Umbria-Marche earthquake in September 1997. Subsequent restoration included a seismic retrofit using both traditional and innovative solutions (Croci [8], Bonci [9]), that comprised STUs. The use of STUs in historical structures had been first proposed and applied in Italy more than 10 years before (in the dynamic connection of a new steel roof structure to the masonry walls of a church damaged by the 1980 Irpinia earthquake; see Candela [10]). However, later on, there was only one other application of this type to a structure of historical value. In the Basilica of San Francesco, STUs were used to connect different parts of a steel truss following the perimeter of the Upper Basilica (Figure 17), aimed at stiffening the masonry structure and guarantee its box behaviour despite vertical cracks created by the earthquake near the centre of each bay of the side walls. In order to provide the stiffness needed to withstand an earthquake without inducing undesired forces under service conditions (relative movements due to thermal effects, seasonal water table variations, etc.) the aforesaid truss was subdivided in sub-elements along the nave, each corresponding to a bay of the side wall between two external buttresses, connected to each other through a couple of STUs (each with a design force of 220 kN), installed behind the pillars (Figure 18). To connect the main facade to the orthogonal walls, three STUs (each with design force of 300 kN) for each wall were used (Figure 19).
Owing to the location of the truss (just above the Giotto frescos and under the windows) special care was exercised in the selection of STU materials, to reduce dimensions, increase durability and avoid any risk of fluid percolation. High strength stainless steel and high viscosity silicon putty were used.

Figure 17 - The horizontal stainless steel beam all along the Upper Basilica of San Francesco in Assisi (the red circles indicate the position of STUs).

Figure 18 – Two 220 kN STUs installed in the Basilica of San Francesco in Assisi.

Figure 19 - A 300 kN STU installed in the Basilica of San Francesco in Assisi.
CONCLUSIONS

Although their behaviour is different, both fluid viscous dampers and shock transmission units can be used to improve the seismic response of structures. In recent years, their reliability, proven by many instances of application in bridges and demanding qualification tests, has lead to an increase of their use in buildings. They have been used to improve both local and total structural responses. In particular, STUs demonstrated to be very effective in retrofit of stiff structures such as RC shear-type or masonry buildings. The results of acceptance tests performed for many of the projects described above have confirmed the reliability of the aforesaid devices even for the small values of design force and design displacement that often characterize the devices used in buildings.

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