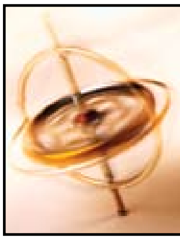
Lateral Load Response Control Using the Gyroscope

By Garen B. Gregorian, P.E. and Zareh B. Gregorian, P.E.

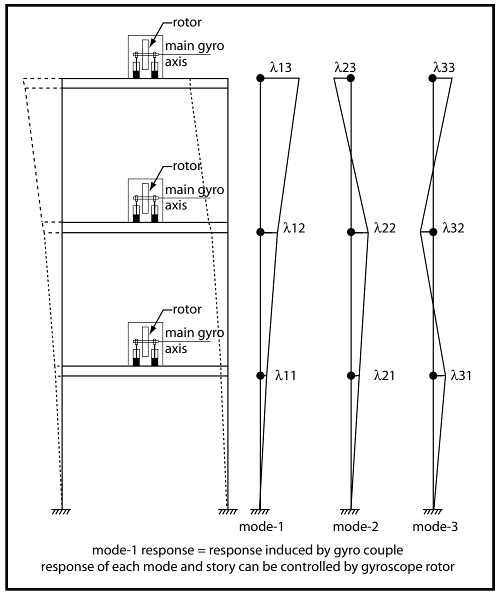


Gyroscope or Gyrostat: *a rigid body that rotates at very large angular speed Omega (Ω) about one of its principal axes of inertia and of which the rotation (ω) about axes perpendicular to this "gyroaxis" are very slow compared to the main rotation Omega.*

The purpose of this article is to introduce the concept of using the gyroscope in the design and stability of multistory structures acted upon by wind or seismic loads.Taking advantage of the angular momentum of the rotating gyroscope actuated during earthquake and wind loads, one can reduce and or control the lateral movement of the structure.

The concept of the gyroscope has been applied to the turbines of ships, the bicycle, the Sperry anti-roll device, the artificial horizon for aircraft, the precession of equinoxes, and can be used to control rocking motion throughout the height or from the base of the structure at the foundation.

Although more suited for controlling wind induced motion, the concept could work as a base isolation system in conjunction with soil improvement and passive or active isolation and screening methods, especially for buildings categorized as occupancy group-IV essential facilities located in highly active seismic zones which fall under seismic design category D, E, and F. The system would be similar to open trenches around the periphery of a foundation used to decrease the displacement amplitude of a propagating wave to within tolerable limits.



Controlling the response of a multistory building using the gyroscope.

Operation of the Gyro

Power actuated and controlled by a "pilot gyro", the rotor can be positioned at an inclined angle to the main gyroscopic axis. This will provide the torque required to compensate and control the deflection and rocking of the structural frame.

The gyroscope rotor, while in operation, will not exert any dynamic loads to the frame when rotating with constant angular velocity. However, if it is quickly accelerated to the desired angular velocity, unwanted lateral and vertical loads will be imposed on the frame. The structural system can be studied and the centrifugal machine force can be idealized with a sinusoidal forcing function to solve for the response. Furthermore, the mechanism would have to be balanced in a timely manner to avoid resonance and the need for response control in the transverse direction.

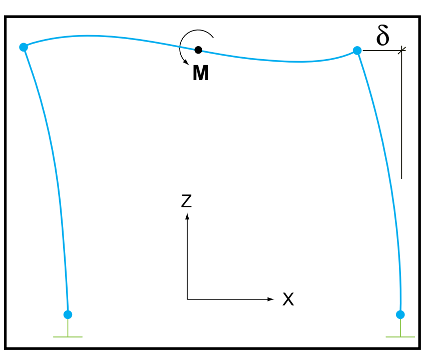


Figure 1: Deflected shape of steel frame.

Taking the equilibrium approach, the rate of change of angular velocity multiplied by the mass moment of inertia of the rotor will provide the force which will deflect the frame if accelerated. The response due to this force can be resisted by the stiffness of the frame.

According to general practice, it would be preferable to locate the gyroscope/turbine mechanism, and any mechanical equipment or machine rooms, as low to the ground floor as possible. This serves to lower the center of mass of the building to help stability and decrease the whip effect. However, properly designed machines could be tuned to control the deflection and drift of the frame, the diaphragm, and the attached elements so as not to exceed the permissible deflection of the attached elements.

Multiple mechanisms could eventually be placed in a core within the building footprint in plan and placed at every story forming a spine within the building. This would direct and control the modal response and provide a response that is closer to the shape function externally imposed during the dynamic analysis process using the generalized coordinate approach.

Design Example

Single degree of freedom system

Procedure for control of deflection of a single story frame:

1) Design the frame for gravity loads including the gyroscope, and calculate the stiffness properties of the SDOF Frame.
2) Redesign the frame calculating the seismic loads which will act on the frame and design the frame for code. Establish the design story drift (i.e.; story drift δ = L/100 to L/500).
3) Determine the moment exerted from the inclined gyroscope, which would displace the frame in the opposite direction to that of the lateral load or deflection.
4) Determine the roll angle which the gyroscope or turbine rotor would have to be inclined.
5) Redesign the frame for the complete system.

Calculate the fundamental period of the SDOF, by simplified method using ASCE 7-02.

The natural period of vibration of the one story building was taken as:

$T_a = C_t h_n^x = 0.028\,(20)^{0.8} = 0.3076$ seconds

f = natural frequency of the structure $2\pi/T$ = $2(3.14)/0.3076$ = 20 radians/sec (3.2 Hertz)

Assuming a tower with a height of 20 feet, and taking the design drift limit for the story as L/300, will give a deflection at the top of the tower equal to 0.8 inches.

Determine the size of the frame members required to support the equipment for gravity loads.

A 25-foot x 25-foot bay was considered for the single story frame with a story height of 20 feet. Steel beams were sized for gravity load as follows:

Dead Load: 100 psf including concrete metal deck and steel framing.

Live load: A live load of 200 psf was chosen for mechanical room loading.

The main girders were preliminarily sized for the total moment of:

$M = WL^2/8 = (300/1000)(12.5)(25)^2/8 = 293$ kip ft as A992 W18x60.

The column loads were calculated as 47 kip floor load and 10 kip turbine load of 57 kips. W10x33 sections were selected using the AISC column table 4-1, with an available strength in axial compression of 95.4 kips.

As the drift limit was set at L/300, next find the moment required to produce this drift.

Determine the roll back angle where the rotor would have to be rotated to produce the moment.

If the roll back angle ϕ is chosen as 20 degrees:

$\phi = 20\,(2)\,\pi/360 = 0.3489$ radians

$\omega = 2\,(\pi/360)\,(1/T)\,10 = 2\,(3.14/360)\,(1/0.05)\,(10) = 3.4889$ radians/sec.

For a turbine with a rotor angular velocity $\Omega = 10{,}000$ rpm $=1050$ radians/sec.

Weight of the turbine itself is approximately 10,000 lbs.

Denoting the mass of the rotor by $m = W/g$ [lb sec^2/in], where ($g = 32.2$ ft/sec^2 $= 384$ in/sec^2)

r = radius of gyration of the rotor = 24 inches.

Mass moment of inertia of the rotor (assuming thin disk): $I = m r^2 = 576\,m$

Assuming the rotor weighs 1,000 pounds; $m = 1000/384 = 2.6$ lb mass.

The gyroscope torque $M = I\,(m)\,(\Omega)\,(\omega) = 576\,(2.6)(1050)\,(3.4889) = 5486208$ lb-in $M = 457$ kip-ft.

Taking the distance between the bearings as 4 feet, the gyroscopic force on the bearings will equal 457/4 =114.296 kips.

For an initial study, a one story moment frame was chosen with a fixed base and analyzed for the 460 kip-ft moment applied at mid span. The analysis assumed a roll angle of 40 degrees; a deflection of 0.44 inches was calculated at the top of the frame due to this moment. (*Figure 1* and *Figure 2*)

Next, the frame was analyzed for two mechanisms installed at each end of the frame, with each turbine having a roll angle of 20 degrees thus generating a moment of 457 kip-ft. The couple was then transferred as a horizontal force by use of knee braces (*Figure 3, page 24*).

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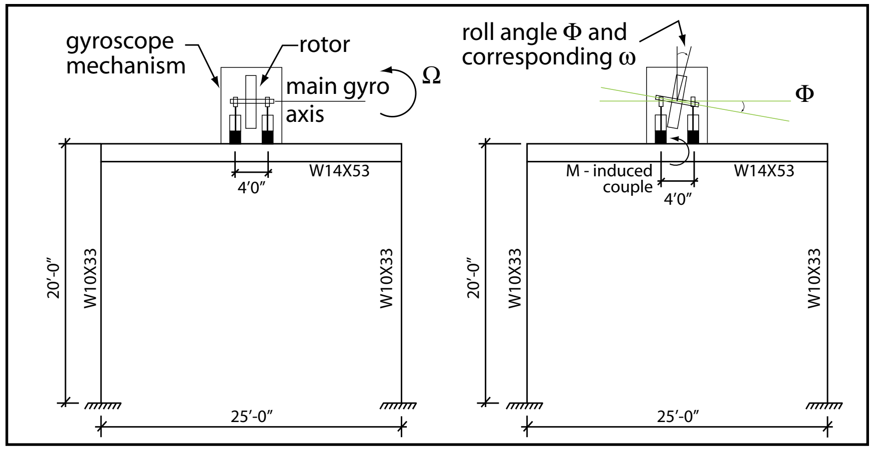
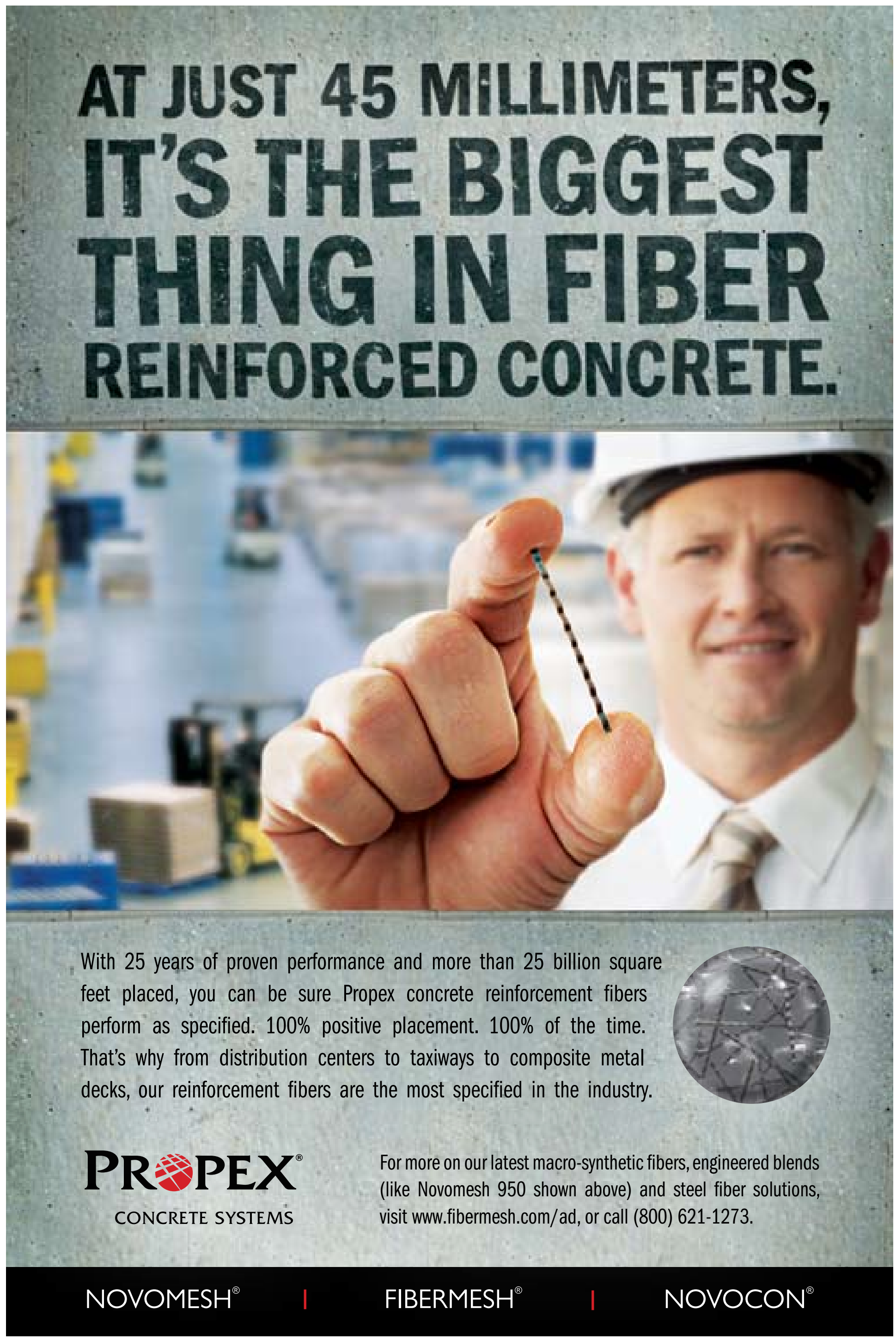


Figure 2 : Steel frame with gyroscope mechanism.



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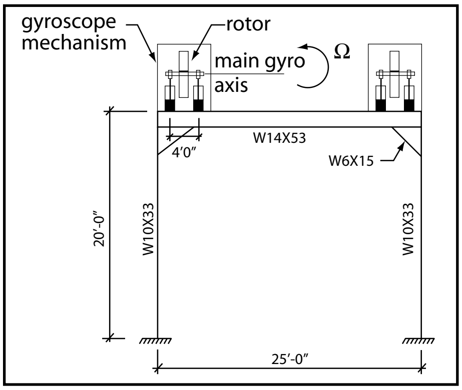
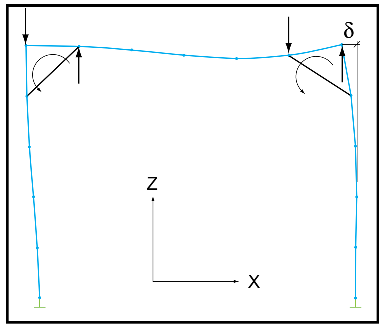
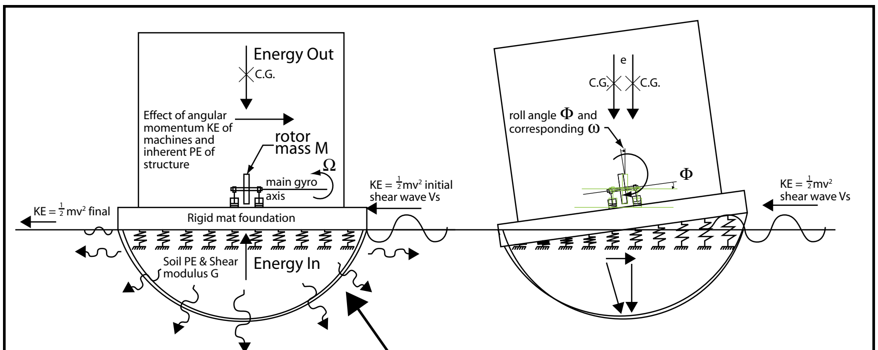


Figure 3: Two mechanisms placed at the support points.



Frame with knee brace solved for couple placed at the support.



a) Structure and gyro modeled on a rectangular mat foundation on an elastic half space to study the energy dissipation and soil structure stability. More energy will be reflected back into the soil.

b) Conventional Method - Structure and gyro modeled on a rectangular mat foundation on an elastic half space or lumped masses with spring constants Kx, or Ky if embedded in soil, analyzed to avoid resonance and equipment malfunction during machine operation.

Figure 4.

The frame was analyzed with inclusion of the knee braces. The 114.29 kip forces of the couple were placed on the support joint and the link between the beam and the knee brace.

The deflection of the frame was calculated as 0.71 inches which is within the tolerable L/300 and L/350 limit. With the stiffness and variables of the machine (I, m and Ω) kept constant, the roll angle and the knee brace dimension can be varied to achieve the desired deflection allowed by code.

Further Research and Applications

Startup operation of the gyroscope, and its effect on the natural period of vibration of the structure to avoid resonance with different site and soil conditions, would require further study using precise prototype models. The rate of change of angular momentum which generates the force can be correlated and synchronized with a site specific acceleration response spectrum, if desired.

The mechanism can also be installed at the interface between the structure and soil to control and stabilize the deflected structure. Using F=m*a, and conservation of energy principles:

Potential Energy (PE) + Kinetic Energy (KE) of incoming seismic wave = PE + KE of soil + Structure, one can take advantage of the kinetic energy of the rotating turbine to decrease the potential energy of the structure. (*Figure 4*)

Eventually, the concept of using centrifugal machines, such as vibration generators to measure movement within the structure, can be applied to control movement. There is a possibility to use existing turbines of mechanical units in high-rise buildings, or power generating facilities turbines, to stabilize the building by offering resistance to rocking and twisting motion.

This mechanism can help respond to changes in the period of the structure due to an increase or decrease in stiffness as a result of retrofit and rehabilitation, such as the addition of new floors, wings or openings.

Until then, as requested by previous authors, hopefully codes such as ASCE 7 will include more accurate, tabulated seismic design forces to determine the base shear. Or, if using modal analysis procedures, a more accurate method of finding K_y, and Kθ for using soil-structure interaction for foundations resting on or embedded in soil, much like the tables used for obtaining design wind pressures on buildings.▪

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