STRUCTURAL INTEGRITY IN EXTREME EARTHQUAKES
THE SWISS FULL BASE ISOLATION SYSTEM (3-D)

by

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SUMMARY

Full Base Isolation FBI (3-D) as antiseismic concept for structures adds vertical flexibility to horizontal base isolation HBI (2-D). Extensive experimental testing at the Swiss Federal Institute of Technology and the University of California, Berkeley, has shown FBI to be a practicable way to reach the final goal of earthquake protection, i.e. elastic behavior of the structural frame in extreme earthquakes. Swiss engineers pioneered base isolation by the construction of the school Pestalozzi at Skopje in 1968. Further development has made Integral Earthquake Protection possible for structures and contents.

INTRODUCTION

The Swiss FBI System, also known as *Seismafloat System*, comprises four components (from top to bottom, FIG. 1):

- the protected superstructure including all equipment and installations
- seismic isolators (3-D) combined with stabilizers
- the foundation
- the participating construction soil

The seismic response mechanism of FBI structures is fundamentally different to conventional fixed base FB structures or to HBI structures. No large structural deformations are required to maintain dynamic equilibrium as in FB structures, nor limits present to horizontal motion typical for vertically unisolated HBI structures. FBI gives nearly unrestricted freedom for 3-D motion of the superstructure relative to the ground. Numerical and test experience show that this modification of the response mechanism is decisive if structures are to withstand all types of extreme earthquakes without destruction in the structural frame nor damage to the contents. This ultimate degree of earthquake safety has been called *Integral Earthquake Protection* (REF. 1).

DIFFICULTIES IN ACHIEVING INTEGRAL EARTHQUAKE PROTECTION

Integral Earthquake Protection means safety in extreme earthquakes against:

1. *Collapse* of structures with low fundamental frequencies in zone B of the site-dependent design spectra (FIG. 2)
2. *Destruction by resonance* effects in structures with medium fundamental frequencies in zone C
3. *Brittle fracture* in structures with high fundamental frequencies in zone D
4. Over-loading in the structural frame due to *differential motions at the support points*
5. *Damage to contents* (equipment and installations within structures)

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So far all attempts to find a conventional technical solution to control or eliminate simultaneously all five classes of damage have lead to a conceptional stalemate. This stalemate can be overcome using FBI (REF. 3).

STANDARD, INTENSE AND EXTREME EARTHQUAKES

FBI is primarily aimed at protecting sensitive and valuable structures potentially exposed to intense and extreme earthquakes. Development of the Swiss System has been based on typical extreme ground motion as described in Appendix A. Those quantities specify peak values of ground motion, limits to the active seismic frequency band, and maximum duration of periods of intense motion to be suitably combined for the relevant earthquake types. Vectorial Seismic Motion Intensity, in short *Motion Intensity MI,* has been used to quantify the seismic reference or guarantee level up to which the structure will be safe when designed as a Seismafloat System.

Typical Motion Intensity values for areas of high seismicity (recurrence period of standard earthquakes 5 to 10 years, intense earthquakes 50 to 100 years, and extreme earthquakes 500 to 1000 years) are:

	metric [m $s^{-2/3}$]	english [in $s^{-2/3}$]
- Standard earthquakes:	$MI < 3.0$	$MI < 120$
- Intense earthquakes:	$3.0 < MI < 6.0$	$120 < MI < 240$
- Extreme earthquakes:	$6.0 < MI < 15.0$	$240 < MI < 600$

All components of the Swiss System can be designed to be safe in extreme earthquakes. The Pacoima Dam record as a large displacement shock and the artificially generated CALTECH A signal as a very long white noise-like earthquake are two typical extreme earthquakes with particularly high motion intensities MI (REF. 2).

THE SEISMAFLOAT SYSTEM

The Seismafloat System (FIG. 1) combines normal construction materials and construction methods with *advanced isolator technology.* A complete joint is required between superstructure and foundation. The vertically supporting elements in the joint region thus will be adapted to accommodate two element types:

A. Highly flexible elements, called *seismic isolators,* that incorporate properties of a combined spring and damper acting in all directions, vertically and horizontally (3-D)

B. Stiff brittle elements, called *mechanical stabilizers,* that transmit wind forces to the ground together with isolators, but break smoothly in predefined earthquake conditions.

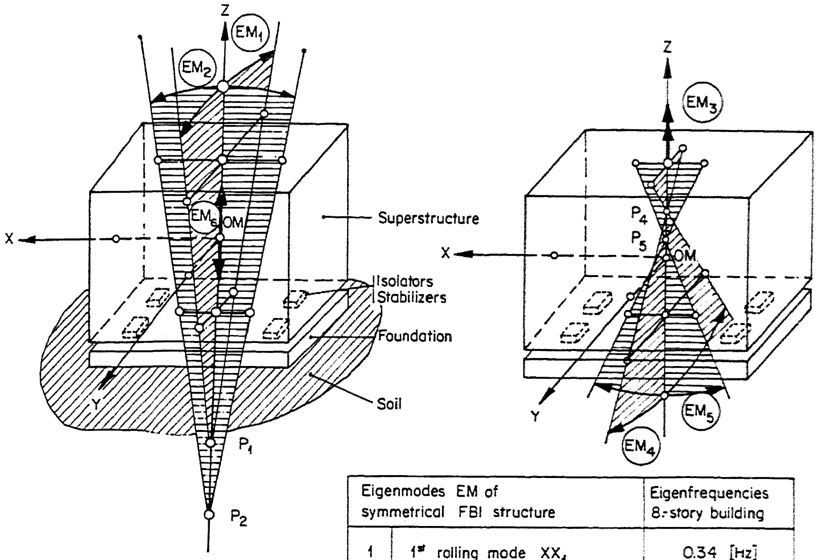
The four system components then have the following characteristics:

Seismic isolators

Seismic isolators control system dynamics by spring and damper properties. Basically, two isolator types may be used:

- vertically and horizontally flexible bearings in natural rubber that combine spring and damper properties in one element
- steel springs combined with independent 3-D damper elements.

In seismic applications *rubber bearings* are superior to steel springs:



Eigenmodes EM of symmetrical FBI structure		Eigenfrequencies 8-story building
1	1st rolling mode XX_1	0.34 [Hz]
2	1st rocking mode YY_1	0.40
3	1st twisting mode ZZ_1	0.44
4	2nd rolling mode XX_2	1.02
5	2nd rocking mode YY_2	1.14
6	1st vertical mode Z_1	1.60

FIG. 1: Concept of Full Base Isolation for structures: 6 fundamental modes and eigenfrequencies of a typical symmetrical 8-story building

Eigenfrequency tuning with Full Base Isolation

Zone B: Fundamental structural eigenfrequencies 1-6

Zone C: Hole of structural eigenfrequencies in the seismic resonance zone

Zone D: Upper structural eigenfrequencies 7, 8, 9....

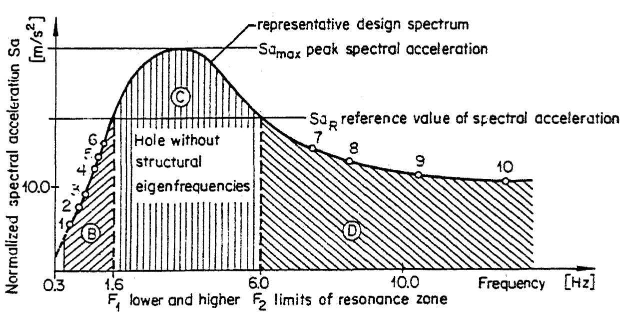


FIG. 2: Elastic behavior of structures in extreme earthquakes made possible by Full Base Isolation and frequency tuning to design spectrum

- Buckling stability, a crucial condition, is warranted in any extreme isolator position.
- Static load capacity is sensibly higher.
- Sufficient damping is provided in all extreme earthquake conditions without additional damper elements.
- Cost per unit supported weight is lower.

A typical extreme earthquake-safe isolator is shown schematically in Appendix B. *Solid natural rubber cylinders* guarantee high axial and radial flexibility. The isolators work in compression, tension, shear, and all rotations. Static load capacity may be varied in a wide range from 400 to > 12000 [KN] (90 to 2600 [kips]). Seismic isolators are designed to accommodate repeatedly dynamic deflections of ± 500 [mm] horizontally and ± 200 [mm] vertically (20 and 8 [in]) in extreme earthquakes. Deflections of ± 800 [mm] horizontally and ± 300 [mm] vertically (32 and 12 [in]) are allowed for a maximum of 3 cycles as a second safety limit. Equivalent damping is 3 to 6 % of critical damping, hysteretic, and particularly well suited for seismic isolation.

Stabilizers

Mechanical stabilizers establish a stiff connection between superstructure and foundation. Thus, structures will react as normal to static loads, wind, and in standard earthquakes; the base isolation system will only be activated in major earthquakes. Secondly, stabilizers limit isolator deflection under static load. These *mechanical fuses* included in the design fail under controlled conditions at an appropriate earthquake level.

In the Swiss System *foam glass elements* rather than the classical shear pins made of steel are used because of their superior performance in 3-D.

Isolators and stabilizers can be readily replaced when needed. In the absense of earthquakes, both element types have a service life of 50 to over 100 years. Mechanical properties are close to stable during that time.

Superstructure

Despite the fact that FBI substantially reduces earthquake forces in the superstructure, they still tend to be relatively high in extreme earthquakes. Higher frequencies have, however, been almost completely eliminated and structural elements can now be designed freely to match occuring forces. A box-like design is recommended with load carrying outside walls, openings of reasonable size, and inner elements (slabs, core, columns, walls) fully integrated in a honeycomb-like, compact, homogeneous body.

Foundation and soil

Extreme earthquake safety requires special attention to the foundation design. Two main solutions are at hand:
- a classical foundation in form of a continuous mat
- a normal basement or ground floor used to implement the isolators.

Quality of construction soil is another important element. In general, the stiffer the soil, the more effective is earthquake isolation. Bedrock and consolidated alluvions are specially suited construction soils.

Finally, design rules for *stiffness tuning* between superstructure, isolators, and construction soil are to be respected. Only all proposed measures together will afford Integral Earthquake Protection (REF. 4).

CONSEQUENCES OF FBI

Gap in the structural frequencies and shift of the active frequency band

FBI modifies fundamentally the vibrational properties of a structure:

1. The isolated superstructure behaves in extreme earthquakes like a flexibly supported rigid body and has the corresponding six modes in space. These modes belong to the *fundamental structural frequencies (1-6)* of the system and may be tuned into zone B of the seismic response spectrum, i.e. lower than the seismic resonance zone C (FIG. 2).
2. All *upper structural frequencies (7, 8, 9 ...)* are tuned into zone D, i.e. higher than the seismic resonance zone C. Modal contribution of upper modes to total earthquake response consequently is minimized and may be neglected for analysis.

Due to consequences 1 and 2 structures do not have frequencies in seismic resonance zone C as is usually the case with normal FB and HBI structures: a *gap without structural frequencies* is achieved.

With FBI low tuning of the structural frequencies, first, reduces substantially amplitudes of the accelerations transmitted to the superstructure, and, secondly, produces a marked *frequency band shift* of the earthquake frequencies still transmitted to the superstructure. Filtering of the higher part of seismic excitation is so effective that no resonance effects must be expected above 2.5 [Hz] if FBI structures are designed to the specifications of the Seismafloat System (FIG. 4).

Reduction of earthquake forces

FBI significantly reduces earthquake forces in structures. Numerical and experimental analyses show that *extreme earthquake safety* can be reached if a structure withstands elastically earthquakes of the intensity level standard earthquakes without the protection system being activated. Activating the FBI system then increases standard earthquake safety to extreme earthquake safety. This means that forces in FBI structures due to extreme earthquakes roughly equal forces of FB structures due to standard earthquakes (REF. 4):

$$F\begin{matrix}\text{isolated structure}\\ \text{extreme earthquakes}\end{matrix} \approx F\begin{matrix}\text{fixed base structure}\\ \text{standard earthquakes}\end{matrix}$$

MATHEMATICAL MODELING AND EXPERIMENTAL TESTING

Combining these three principal consequences of FBI yields structures that behave like rigid bodies even in extreme earthquakes. In addition, mathematical modeling will show in many practical cases that soil/structure interaction is almost nonexistent due to the 3-D highly flexible isolators and if the structure is built on firm soil.

For such structures the *Seismic Mass Analogy* with the six degrees of freedom of a flexibly supported rigid body in space may be used for earthquake analysis. Very accurate results have been obtained in complete 3-D analyses that are comparable in precision to highly refined finite element models (REF. 4).

In a joint Swiss-American research program extensive *shake table tests* could be realized at the Earthquake Engineering Research Center EERC of the University of California, Berkeley. In April 1982, a large model of a hospital was tested on the 2-D EERC shake table (FIG. 3,4). More than 70 test runs have been executed, more than 20 of them were actual extreme earthquakes such as the Pacoima Dam and the CALTECH A signal. The Seismafloat System has proven its unrestricted isolation capacity in all conditions considered.

COST OF FBI

Implementation of FBI in an 8-story office building accommodating, for instance, expensive computer equipment, or in a hospital with large operation facilities will cost about 5 to 10 % of raw construction (structural frame and foundation). Raw construction cost, as a statistical mean, is roughly 1/3 of the total building investment. Complete nuclear power plants built with FBI on one large base mat are expected to be less expensive - and considerably more safe - than conventionally designed plants.

CONCLUSION

Integral Earthquake Protection of structures means *elastic behavior of the structural frame* in extreme earthquakes. It can be practically realized by Full Base Isolation of the structure according to the Seismafloat System. Extensive analytical, numerical, and experimental research at the Swiss Federal Institute of Technology has established that the Swiss System for Full Base Isolation yields elastic behavior in the strongest foreseeable earthquakes. Shake table tests at the Earthquake Engineering Research Center of the University of California have fully confirmed this capacity.

ACKNOWLEDGEMENTS

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REFERENCES

REF. 1-4: Staudacher K.: "Integral Earthquake Protection of Structures": Swiss Federal Institute of Technology Zürich, IBK; Switzerland; 1981/82.
Part I: "Philosophy of Protection - Central Concepts - Numerical verification"
Part II: "Defining the Loading Case Earthquake"
Part III: "Earthquake Protection at a Turning-Point?"
Part IV: "Full Base Isolation and Seismic Mass Analogy"
REF. 5: Staudacher K., Kelly J.M.: "Extreme Earthquake Safety by Full Base Isolation: Shake table tests on a 5-story building, scale 1:3"; Earthquake Engineering Research Center, University of California, Berkeley; USA; to appear.

APPENDIX A: SEISMIC DESIGN VALUES FOR THE SWISS FBI SYSTEM

Peak values of ground motion (all values are vectorial quantities)

	metric	english
peak acceleration	3.0 - 20.0 [m/s^2]	0.3 - 2.0 [g]
peak velocity	1.0 - 1.5 [m/s]	40.0 - 60.0 [in/s]
peak displacement	1.2 - 0.4 [m]	50.0 - 15.0 [in]

Values on the left: soft soil, on the right: sound rock (REF. 2).

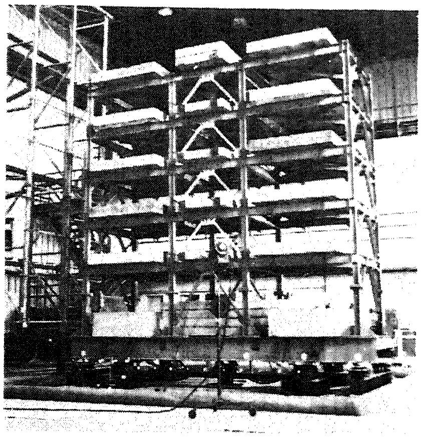
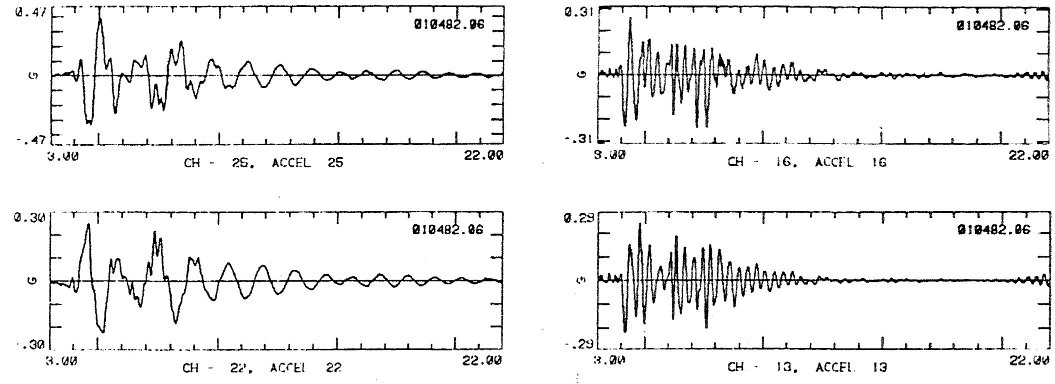
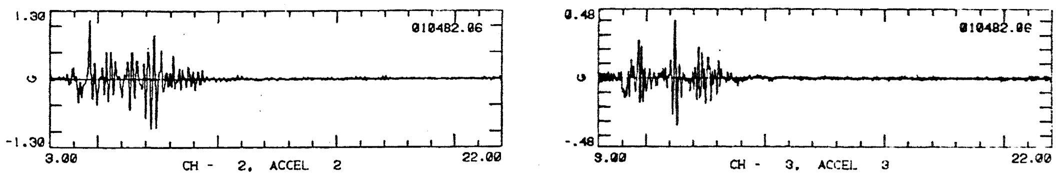


FIG. 3: Shake table tests with 5-story model (scale 1:3) at Univ. of California, Berkeley: Seismafloat System with steel frame of 360 [KN]/ 80 [kips], solid natural rubber bearings, foam glass stabilizers



Horizontal structure response in center of superstructure (channel 22) and upper right corner (channel 25)

Vertical structure response in center of superstructure (channel 13) and upper right corner (channel 16)



Horizontal table acceleration

Vertical table acceleration

FIG. 4: Shake table tests with 5-story model: Vert/horiz structure response to table input - Pacoima Dam record (Feb. 9/71, time scale 1:1.73)

Frequency band of seismic resonance zone

The seismic resonance zone C, FIG. 2, is defined by $Sa_R = 0.8\ Sa_{max}$ as reference value of peak spectral acceleration. Lower and upper frequency limits F_1, F_2 depend on peak soil deformation and lower with large deformations.

Frequency band ($F_1 - F_2$) of seismic resonance zone C:
rock 2.0 - 7.0 [Hz]; stiff soil 1.6 - 6.0 [Hz]; deep soil without cohesion 1.6 - 5.0 [Hz]; soft to medium stiff sandy clay 0.8 - 2.0 [Hz].

Maximum duration of period of intense motion

The period of intense motion $TT = T_2 - T_1$ is defined by a reference acceleration $\ddot{X}_R = 0.5\ \ddot{X}_{max}$, $\ddot{X}_R$ beeing half of peak acceleration $\ddot{X}_{max}$.

Maximum duration of period of intense motion:

Short, shock-like extreme earthquakes	$TT < 10$ [s]
Long, white noise-like extreme earthquakes	$TT < 120$ [s]

APPENDIX B: 3-D SEISMIC ISOLATORS (NATURAL RUBBER) FOR FBI

Accepted deformations

dynamic-repeatedly: (from position at rest)

$\Delta l_{r,s} = \pm\ 500$ [mm] = ± 20 [in]

$\Delta l_t = \pm\ 200$ [mm] = ± 8 [in]

Natural rubber damping

markedly hysteretic, deformation dependent, equivalent damping:
3 - 6 %

Standard size for extreme earthquakes

(depends on seismic risk and static load)

static: $-10 \le \varepsilon_t \le -24$ [%]

dynamic-to 3 cycles:

$\Delta l_{r,s} = \pm\ 800$ [mm] = ± 32 [in]

$\Delta l_t = \pm\ 300$ [mm] = ± 12 [in]

Static load capacity

400 - 12000 [KN]
= 90 - 2600 [kips]