



Seismic Conceptual Design of Buildings – Basic principles for engineers, architects, building owners, and authorities

Hugo Bachmann



Bundesamt für Wasser und Geologie **BWG**
Office fédéral des eaux et de la géologie **OFEG**
Ufficio federale delle acque e della geologia **UFAEG**
Uffizi federal per aua e geologia **UFAEG**
Federal Office for Water and Geology **FOWG**

Federal Department of Foreign Affairs (DFA)

Federal Department of the Environment, Transport, Energy and Communications (DETEC)

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Author's Preface

For a long time earthquake risk was considered unavoidable. It was accepted that buildings would be damaged as a result of an earthquake's ground shaking. Preventive measures for earthquakes were therefore mostly limited to disaster management preparedness. Although measures related to construction methods had already been proposed at the beginning of the 20th century, it is only during the last decades that improved and intensified research has revealed how to effectively reduce the vulnerability of structures to earthquakes.

The objective of this document is to present recent knowledge on earthquake protection measures for buildings in a simple and easy to understand manner.

The chosen method explains basic principles by matching them with illustrations, examples, and an explanatory text. The principles, photographs (from the author or third parties), and the texts are the result of a long research and design activity in the challenging and strongly evolving field of earthquake engineering.

The author would like to thank, above all, the numerous photographs contributors mentioned at the end of the booklet, who have made available the results of extensive and often dangerous efforts. Thanks are also extended to the Federal Office for Water and Geology and the Swiss Agency for Development and Cooperation for editing and carefully printing this document.

Zurich, December 2002

Prof. Hugo Bachmann

Editor's Preface

Worldwide earthquakes cause regularly large economic losses - Kobe in 1995 with more than 6000 casualties, counted for 100 Billion US\$ of economic loss. Earthquakes are unavoidable. Reducing disaster risk is a top priority not only for engineers and disaster managers, but also for development planners and policy-makers around the world. Disaster and risk reduction are an essential part of sustainable development.

On December 11 2000, the Swiss Federal Council approved for federal buildings a seven-point program running from 2001 to 2004 for earthquake damage prevention. The earthquake resistance of new structures is a high priority in the Confederation's seven-point program. The author of this publication, Professor Hugo Bachmann, has devoted many years to the study of seismic risk and behavior of buildings subjected to earthquakes. At the request of the FOWG, which expresses its gratitude to him, he agreed to make available his extensive scientific knowledge on earthquake resistance of buildings. These guidelines are designed to contribute to the transfer of research results into building practice. These results must be

taken into account by the design professionals, thus ensuring a reasonable earthquake resistance for new structures at little or no additional cost.

SDC would like to contribute to the dissemination of knowledge on seismic design of buildings by translating this FWOG publication in English and thus extending its readership among construction professionals. SDC intends to gather available experience in the domains of construction and prevention of natural hazards and technical risks and to make it accessible to the practitioners in developing and transition countries in an easy to understand form.

Biel, December 2002

Dr Christian Furrer
Director of the Federal Office
for Water and Geology (FOWG)

Bern, December 2002

Ambassador Walter Fuest
Director of the Swiss Agency
for Development and Cooperation (SDC)

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Objectives

This document offers a broad outline of the art of designing earthquake resistant buildings. It describes basic principles guiding the seismic design of structures. These principles govern primarily the:

- **Conceptual design**, and the
- **Detailing**

of

- **Structural elements** and
- **Non-structural elements**

The conceptual design and the detailing of the structural elements (walls, columns, slabs) and the non-structural elements (partition walls, façades) plays a central role in determining the structural behaviour (before failure) and the earthquake vulnerability (sensitivity to damage) of buildings. Errors and defects in the conceptual design cannot be compensated for in the following calculations and detailed design of the engineer. A seismically correct conceptual design is furthermore necessary in order to achieve a good earthquake resistance without incurring significant additional costs.

The outlined principles are thus primarily applicable to new buildings. However, it is quite clear that they may also be used for the evaluation and possible upgrading of existing buildings. Therefore, certain principles are illustrated with applications to existing buildings.

The basic principles are intentionally simple. Calculations and detailed design are only marginally introduced. Additional information may be found in specialised literature (eg. [Ba02]).

The ideas and concepts of the basic principles were developed within a framework consisting of numerous presentations given by the author between 1997 and 2000, the contents of which were constantly elaborated and developed. Each principle is introduced by a schematic figure (synthesis of the principle), followed by a general description. Further illustration is usually provided by photographs of damage, giving either positive or negative examples, and accompanied by a specific legend.

The basic principles (BP) are grouped according to the following subjects:

- collaboration, building codes and costs (BP 1 to BP 3)
- lateral bracing and deformations (BP 4 to BP 20)
- conceptual design in plan (BP 21 to BP 22)
- detailing of structural elements (BP 23 to BP 27)
- foundations and soil (BP 28 to BP 31)
- non-structural elements and installations (BP 32 to BP 35)

It is obvious that not all the basic principles are of the same importance, neither in a general context nor in relation to a particular object. Compromises, based on engineering judgement, may be admissible depending on the hazard level (regional hazard and site effect) and the characteristics of the structure. Of primary importance is the strict adherence to the principles relevant to life safety, particularly those concerning lateral bracing. Only principles primarily intended to reduce material damage may possibly be the subject of concessions.

This document is predominantly addressed to construction professionals such as civil engineers and architects, but also to building owners and authorities. It is suitable both for self-study and as a basis for university courses and continued education. The illustrations may be obtained from the editor in electronic format. All other rights, in particular related to the reproduction of illustrations and text, are reserved.

What happens during an earthquake?

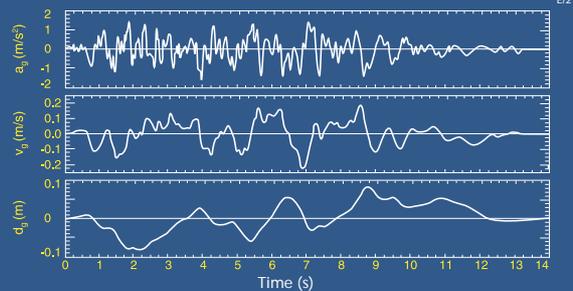
What happens during an earthquake?

- Rapid ground-motion:
 - How long?
 - How much?
- Structural (Building) response:
 - Strong vibrations
 - Large stresses and strains
 - Local failure
 - Total failure = Collapse

Prof. Hugo Bachmann

ibk - ETH Zurich

Time history of ground motion parameters



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In an earthquake, seismic waves arise from sudden movements in a rupture zone (active fault) in the earth's crust. Waves of different types and velocities travel different paths before reaching a building's site and subjecting the local ground to various motions.

The ground moves rapidly back and forth in all directions, usually mainly horizontally, but also vertically. What is the duration of the ground motions? For example, an earthquake of average intensity lasts approximately 10–20 seconds, a relatively short duration. What is the maximum amplitude of the motions? For example, for a typical «Valais Quake» of an approximate magnitude of 6 (similar to the earthquake that caused damage in the Visp region in 1855), the amplitudes in the various directions of the horizontal plane can reach about 8, 10, or even 12 cm. During an earthquake of magnitude 6.5 or more (similar to the «Basel Quake» that destroyed most of the city of Basel and its surroundings in 1356), ground displacements can reach 15-20 cm, and perhaps somewhat more.

What happens to the buildings? If the ground moves rapidly back and forth, then the foundations of the building are forced to follow these movements. The upper part of the building however «would prefer» to remain where it is because of its mass of inertia. This causes strong vibrations of the structure with resonance phenomena between the structure and the ground, and thus large internal forces. This frequently results in plastic deformation of the structure and substantial damage with local failures and, in extreme cases, collapse.

The effects of an earthquake on a building are primarily determined by the time histories of the three ground motion parameters; ground acceleration (a_g), velocity (v_g), and displacement (d_g), with their specific frequency contents. Looking at the example of the linear horizontal ground motion chart of an artificially generated «Valais Quake», it is clear that the dominant frequencies of acceleration are substantially higher than those for velocity and much higher than those for displacement.

The ground motion parameters and other characteristic values at a location due to an earthquake of a given magnitude may vary strongly. They depend on numerous factors, such as the distance, direction, depth, and mechanism of the fault zone in the earth's crust (epicentre), as well as, in particular, the local soil characteristics (layer thickness, shear wave velocity). In comparison with rock, softer soils are particularly prone to substantial local amplification of the seismic waves. As for the response of a building to the ground motion, it depends on important structural characteristics (eigenfrequency, type of structure, ductility, etc).

Buildings must therefore be designed to cover considerable uncertainties and variations.

The most important natural risk

Earthquakes of large magnitudes can often be classified as great natural catastrophes. That is to say that the ability of a region to help itself after such an event is distinctly overtaxed, making interregional or international assistance necessary. This is usually the case when thousands of people are killed, hundreds of thousands are made homeless, or when a country suffers substantial economic losses, depending on the economic circumstances generally prevailing in that country.

The 2001 Gujarat earthquake is a recent example of such a catastrophe. It was the first major earthquake to hit an urban area of India in the last 50 years. It killed 13'800 people and injured some 167'000. Over

230'000 one- and two-story masonry houses collapsed and 980'000 more were damaged. Further, many lifelines were destroyed or severely damaged and de facto non-functional over a long period of time. The net direct and indirect economic loss due to the damage and destruction is estimated to be about US\$ 5 billion. The human deaths, destruction of houses and direct and indirect economic losses caused a major setback in the developmental process of the State of Gujarat.

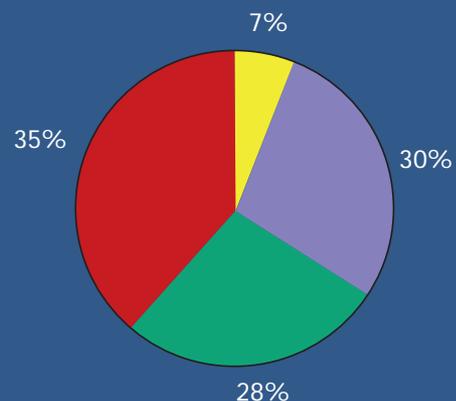
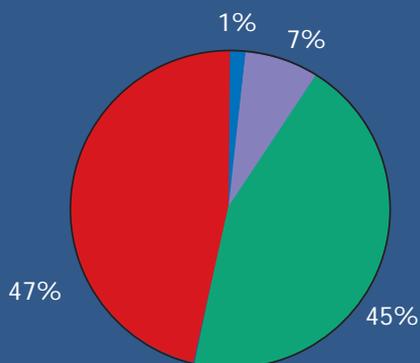
From 1950 to 1999, 234 natural catastrophes were categorized as great natural catastrophes [MR 00]. From these 234, 68 (29%) were earthquakes. The most important ones in terms of loss of lives were the 1976 Tangshan earthquake (China), with 290'000 fatalities and the 1970 Chimbote earthquake (Peru), with 67'000 fatalities. In terms of economic losses, the

Great natural catastrophes 1950-1999

Fatalities: 1.4 mio

Economic losses: US\$ 960 bn

E/3



■ Earthquakes ■ Windstorms ■ Floods ■ Others

Munich Re Group, 2000

most important ones were the 1995 Kobe earthquake (Japan), with US\$ 100 billion, and the 1994 Northridge earthquake (USA) with US\$ 44 billion.

In terms of loss of lives and economic losses, it can be seen on the figure of page 8 that earthquakes represent the most important risk from natural hazards worldwide. It is tempting to think that this risk is concentrated only in areas of high seismicity, but this reasoning does not hold. In regions of low to moderate seismicity earthquakes can be a predominant risk as well. There, hazard can be seen as relatively low, but vulnerability is very high because of the lack of preventive measures. This combined leads to a high risk.

Devastating induced hazards

Apart from structural hazards due to ground shaking, extensive loss can be caused by the so-called induced hazards such as landslides, liquefaction, fire, retaining structure failures, critical lifeline failures, tsunamis and seiches.

For example, the 2001 San Salvador earthquake induced 16'000 landslides causing damage to 200'000 houses. In the 1970 Chimbote earthquake (Peru), a gigantic landslide triggered by the earthquake caused 25'000 fatalities, more than a third of the total fatalities. In the 1906 San Francisco earthquake, most of the damage was caused by uncontrolled fire. In the 1995 Kobe earthquake fire was responsible for 8% of the destroyed houses.

The seismic risk keeps increasing

The seismic risk is equal to the product of the hazard (intensity/probability of occurrence of the event, local soil characteristics), the exposed value and the vulnerability of the building stock. The current building stock is constantly enlarged by the addition of new buildings, many with significant, or even excessive, earthquake vulnerability. This is above all due to the fact that for new buildings, the basic principles of earthquake resistant design and also the earthquake specifications of the building codes, are often not followed. The reason is either unawareness, convenience or intentional ignorance. As a result, the earthquake risk continues to increase unnecessarily.

Urgent action is needed

The preceding remarks clearly illustrate that there is a large deficit in the structural measures for seismic protection in many parts of the world. There is an enormous pent up demand and accordingly a need for urgent action. New buildings must be designed to be reasonably earthquake resistant to prevent the constant addition of new vulnerable structures to a building stock that is already seriously threatened. To this end, the present publication aims at contributing by spreading the appropriate basic knowledge.

BP 1 The architect and the engineer collaborate from the outset!

Basic principles for the seismic design of buildings

1

The architect and engineer collaborate from the outset!

Prof. Hugo Bachmann ibk - ETH Zurich

Basic principles for the seismic design of buildings

1/2

Wrong:
«Serial-design»

1. Architect: Conceptual design of structure and non-structural elements	1. Structure for gravity loads
2. Engineer: Calculations...	2. Non-structural elements
	3. Structure for seismic action

Much better and more economical:
«Parallell-design»

• The architect and engineer collaborate	• General purpose structure and non-structural elements
--	---

Prof. Hugo Bachmann ibk - ETH Zurich

Many building owners and architects are still of the mistaken opinion that it is sufficient to include the civil engineer only at the end of the design stage to «calculate» the structure. This is a bad approach that may have serious consequences and cause significant additional costs. Even the cleverest calculations and detailed design cannot compensate for errors and defects in the conceptual seismic design of the structure or in the selection of non-structural elements, in particular partition walls and facade elements.

the engineer produces a safe, efficient and economical structure. This is why collaboration between the architect and the engineer must start at the first design draft!

«Serial-design» is particularly bad and inefficient. It is not at all efficient that the architect performs the conceptual design and selects the types and materials of the non-structural partition walls and façade elements before entrusting the engineer with the calculations and detailed design of the structure. It is also wrong to consider seismic loading only after completing the gravity load design and selecting the non-structural elements. By then the structure can only be «fixed» for earthquakes. This will often result in an expensive and unsatisfactory patchwork.

Basic principles for the seismic design of buildings

1/1

Even the cleverest calculations and detailed design cannot compensate for errors and defects in the conceptual seismic design of the structural and non-structural elements!

→ Close collaboration between architect and civil engineer from the earliest planning stage!

Prof. Hugo Bachmann ibk - ETH Zurich

A «parallell-design» is much better and usually substantially more economical. The architect and the engineer design together and, taking into account the relevant aesthetic and functional requirements, develop a safe, efficient, and economical «general-purpose» structure for gravity loads and seismic action. They then together select non-structural partition walls and facade elements with deformation capacities compatible with the designed structure. An optimum result can be obtained through this approach. A close and thoughtful collaboration between the architect and the engineer is therefore also of interest to the building owner. This collaboration cannot wait for the calculation and detailed design stage, but must start at the earliest conceptual design stage when choices are made that are crucial for the seismic resistance and vulnerability of the building.

It is important that there is a close collaboration between the architect and the engineer from the earliest planning stage of any building project in order to ensure a good outcome, guarantee structural safety, reduce vulnerability, and limit costs. By doing so, both partners contribute with different, yet indispensable, expertise. The architect deals primarily with the aesthetic and functional design, while

BP 2 Follow the seismic provisions of the codes!

Basic principles for the seismic design of buildings

2

Internationally harmonized standards:
ISO 3010
International Building Code (IBC)
Uniform Building Code (UBC)
Eurocode 8

National standards:
SIA 261 (Switzerland)
IS 1893 (India)
DIN 4149 (Germany)
PS 92 (France)
....

Follow the seismic provisions of the codes!

T. Wenk

In the early 20th century, the first seismic provisions in building codes were introduced in a few countries with high seismicity. These early seismic codes have been periodically updated with increasing knowledge in earthquake engineering. In the 1960's and 1970's, countries with moderate seismicity began to adopt seismic requirements in their building codes. In the same period, the better understanding of dynamic soil behavior as well as inelastic structural behavior led to the development of more advanced seismic codes.

Today, the principles of capacity design together with the concepts of ductile behavior allow a safe and cost effective earthquake resistant design. The latest efforts of seismic code development were mainly focused on internationally harmonized standards like ISO 3010, Eurocode 8, and UBC.

Unfortunately, even today, the seismic provisions of the building codes are not always respected; this is due to either ignorance, indifference, convenience, or negligence. Moreover, appropriate official controls and checks are lacking. Buildings that are very vulnerable and at risk from even a relatively weak earthquake continue to be built today. Investigations of existing buildings (e.g. [La 02]) showed however, that enforcing the building code requirements makes it possible to significantly reduce the seismic vulnerability of buildings with no significant additional costs while improving their resistance against collapse.

The ignorance or disregard of the seismic provisions of the building codes, even if only partial, can result in an inferior building [Sc 00]. The reduction in value may include, among other things, the costs of retrofitting minus the additional costs that would have been incurred to ensure the seismic resistance of the building at its design and construction stage. The designers can be responsible for retrofitting costs, as well as jointly liable with the building owners for loss of life, injury or for any resulting material damage in the case of an earthquake. A retrofit generally costs several times more than what it would have cost to ensure adequate seismic resistance of the new building. Considerable costs may also be incurred by disruptions of the building's use, such as temporary evacuation and business interruption. Furthermore, determining the responsibility of the architect and engineer can necessitate lengthy and complex legal procedures. The building owner, the architect, the engineer, and the authorities therefore have a vested interest in ensuring that the seismic provisions of the building codes are strictly enforced, and that appropriate structural calculations and verifications are kept with the construction documents.



2/1 Buildings are still built for which no verification of adequate seismic resistance is conducted in accordance with the current building codes. In the case of this masonry building, it appears that no adequate measures (e.g. reinforced structural concrete walls) were taken. An insufficient earthquake resistance may cause a significant reduction in the value of the building, and may be the cause of a civil liability lawsuit (Switzerland, 2001).



2/2 Buildings in which the lateral bracing is missing or highly eccentric, or buildings with discontinuities, generally do not satisfy the requirements of the current building codes and are therefore likely to be damaged or collapse under the effect of even a relatively weak earthquake (Switzerland 2000).

BP 3 No significant additional costs thanks to modern methods!

Basic principles for the seismic design of buildings

3

The costs of earthquake resistance depends on:

- planning approach
- applied method

No significant additional costs thanks to modern methods!

Prof. Hugo Bachmann

ibk - ETH Zurich

The opinion that designing new buildings to be earthquake resistant will cause substantial additional costs is still common among the construction professionals. In a Swiss survey, estimates between 3 and 17% of the total building costs were given. This opinion is unfounded. In a country of moderate seismicity, adequate seismic resistance of new buildings may be achieved at no, or no significant, additional cost.

However, the expenditure needed to ensure adequate seismic resistance may depend strongly on the approach selected during the conceptual design phase and on the relevant design method:

- Regarding the conceptual design phase, early collaboration between the architect and civil engineer is crucial (see BP 1). Seismic protection must be taken into consideration in the architectural design of the building as well as in the conceptual design of the structure. Above all, substantial extra costs may be incurred if modifications and additions to the structure need to be made at an advanced stage, since they often require modifications of the architectural design also. These may be very costly.
- Concerning the design method, it should be stated that significant progress has been made recently. Intensive research has improved the understanding of the behaviour of a building or structure during an earthquake and resulted in the development of more efficient and modern design methods. Compared to older methods, the cost of seismic resistance of a building is reduced and / or the performance during an earthquake is notably improved, thus also reducing vulnerability. Of special importance are ductile structures and the associated

design method named capacity design method. Thus, structural elements such as reinforced concrete walls, which are used for wind bracing, can perform other functions without notable additional cost (e.g. by modifying the reinforcement). Fewer additional structural elements are therefore required in comparison to older methods.

Information on the application and advantages of modern methods can be found in the publication [D0171]. This document describes the seismic design of a seven storey residential and commercial building. It enables a comparison between the deformation-oriented capacity design and conventional design (earlier method). The advantages of the modern method for this example can be summarised as follows (see also page 14):

- drastic reduction in the seismic design forces at ultimate limit state;
- better resistance against collapse;
- good deformation control;
- prevention of damage for earthquakes up to a chosen intensity (damage limit state earthquake);
- larger flexibility in case of changes in building use;
- practically equal costs.

The last three advantages are particularly important to the building owner. The larger flexibility with respect to the changes in building use results primarily from the fact that the majority of the walls can be modified or even removed without any problem.

Page 14

3/1 Results of the seismic design of a seven storey residential and commercial building by different methods [D0171].

Seismic conventional design

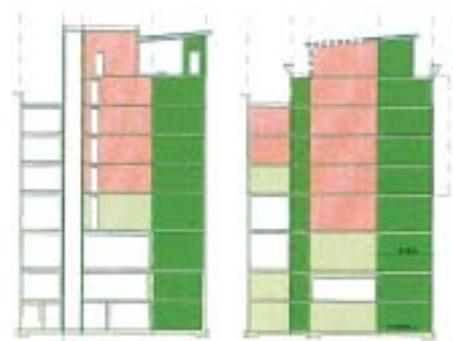
West façade



Section C

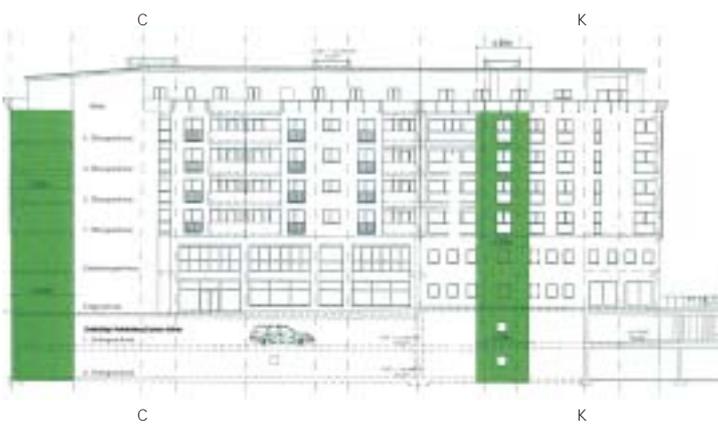
Section H

4. floor
3. floor
2. floor
1. floor
mezzanine
ground floor
1. basement
2. basement



Seismic conceptual design and capacity design

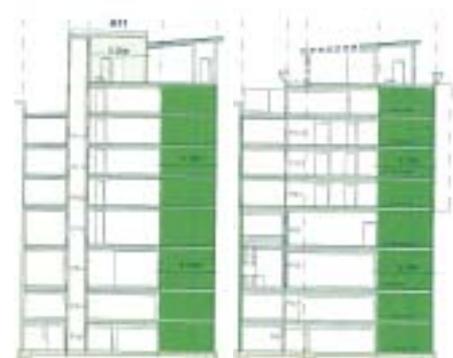
West façade



Section C

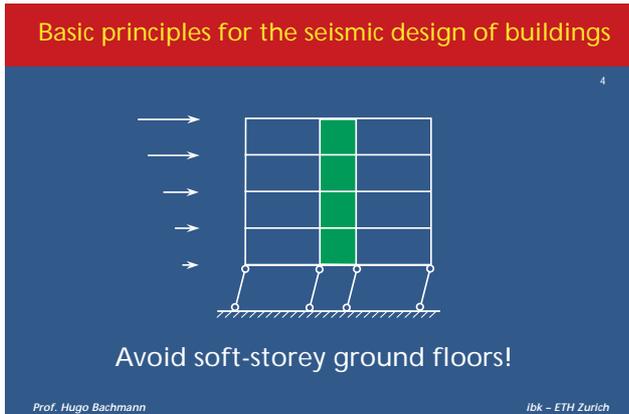
Section K

4. floor
3. floor
2. floor
1. floor
mezzanine
ground floor
1. basement
2. basement



- Walls, slabs, main beams and columns in reinforced concrete to resist gravity loads
- Reinforced concrete walls and frames to resist earthquake actions
- Structural masonry

BP 4 Avoid soft-storey ground floors!



Many building collapses during earthquakes may be attributed to the fact that the bracing elements, e.g. walls, which are available in the upper floors, are omitted in the ground floor and substituted by columns. Thus a ground floor that is soft in the horizontal direction is developed (soft storey). Often the columns are damaged by the cyclic displacements between the moving soil and the upper part of the building. The plastic deformations (plastic hinges) at the top and bottom end of the columns lead to a dangerous sway mechanism (storey mechanism) with a large concentration of the plastic deformations at the column ends. A collapse is often inevitable.



4/1 This sway mechanism in the ground floor of a building under construction almost provoked a collapse (Friaul, Italy 1976).



4/2 Sway mechanisms are often inevitable with soft storey ground floors (Izmit, Turkey 1999).



4/3 Here the front columns are inclined in their weaker direction, the rear columns have failed completely (Izmit, Turkey 1999).

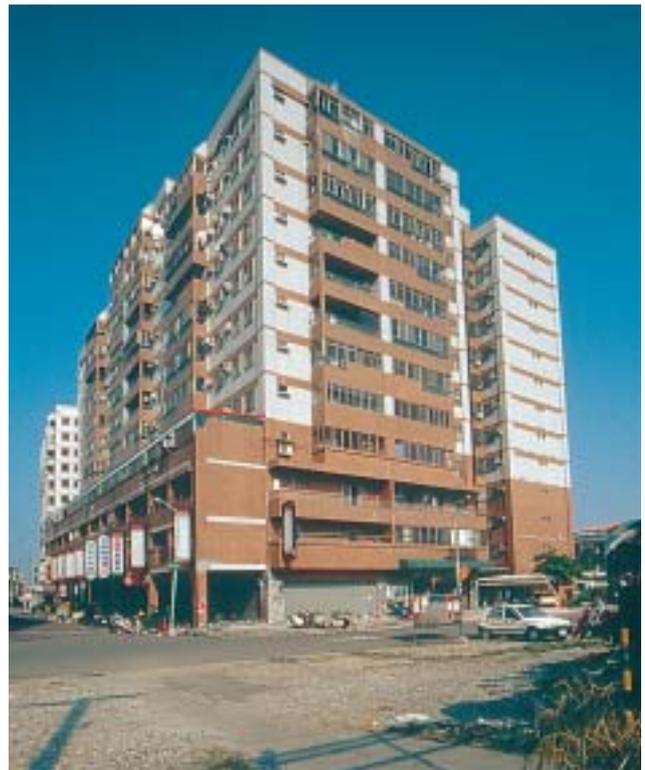
Page 16

4/4 This residential building is tilted as a result of column failure (Taiwan 1999).





4/5 The well-braced upper part of the building collapsed onto the ground floor...



4/7 This multi-storey building escaped collapse by a hair's-breadth...



4/6 ... and these are the remains of the left edge ground floor column (Kobe, Japan 1995).



4/8 ... thanks to resistant columns with well detailed stabilising and confining reinforcement (Taiwan 1999).

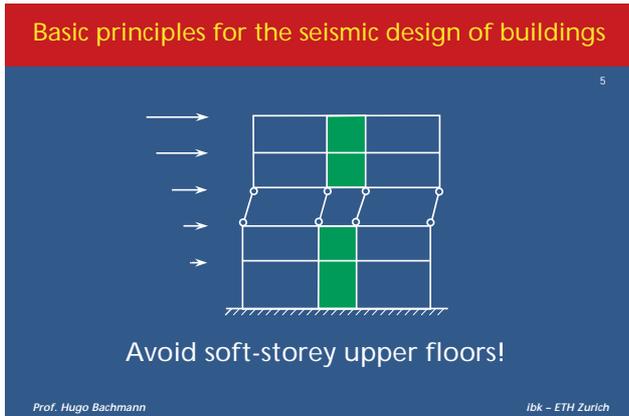


4/9 It is feared that existing buildings such as this one could collapse under even a relatively weak earthquake (Switzerland 2000).



4/10 Likewise, it is probable that the slender columns under the cladding of this existing building are too weak. A few horizontally short reinforced concrete structural walls could help significantly (Switzerland 1998).

BP 5 Avoid soft-storey upper floors!



An upper storey can also be soft in comparison to the others if the lateral bracing is weakened or omitted, or if the horizontal resistance is strongly reduced above a certain floor. The consequence may again be a dangerous sway mechanism.



5/1 In this commercial building the third floor has disappeared and the floors above have collapsed onto it (Kobe, Japan 1995).



5/2 In this office building also, an upper storey failed. The top of the building has collapsed onto the floor below, the whole building rotated and leaned forwards.

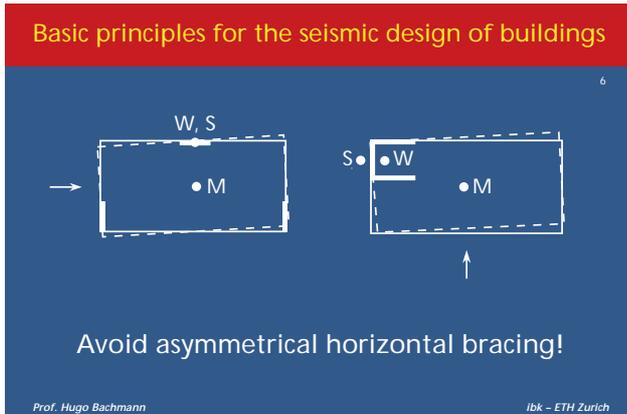


5/3 This close-up view shows the crushed upper floor of the office building (Kobe, Japan 1995).



5/4 All the upper floors were too soft (Izmit, Turkey 1999).

BP 6 Avoid asymmetric bracing!



Asymmetric bracing is a frequent cause of building collapses during earthquakes. In the two above sketches only the lateral bracing elements are represented (walls and trusses). The columns are not drawn because their frame action to resist horizontal forces and displacements is small. The columns, which «only» have to carry the gravity loads, should however be able to follow the horizontal displacements of the structure without losing their load bearing capacity.

Each building in the sketch has a centre of mass M («centre of gravity» of all the masses) through which the inertia forces are assumed to act, a centre of resistance W for horizontal forces and a centre of stiffness S (shear centre). The point W is the «centre of gravity» of the flexural and frame resistance of structural elements along the two major axes. If the centre of resistance and the centre of mass do not coincide, eccentricity and twisting occur. The building twists in the horizontal plane about the centre of stiffness. In particular, this torsion generates significant relative displacements between the bottom and top of the columns furthest away from the centre of stiffness and these often fail rapidly. Therefore the centre of resistance should coincide with, or be close to, the centre of mass, and sufficient torsional resistance should be available. This can be achieved with a symmetric arrangement of the lateral bracing elements. These should be placed, if possible, along the edges of building, or in any case sufficiently far away from the centre of mass.

6/1 In this new skeleton building with flat slabs and small structural columns designed to carry gravity loads, the only bracing against horizontal forces and displacements is a reinforced concrete elevator and stairway shaft, placed very asymmetrically at the corner of the building. There is a large eccentricity between the centres of mass and resistance or stiffness. Twisting in the plan will lead to large relative displacements in the columns furthest away from the shaft and the danger of punching shear failure that this implies. Placing a slender reinforced concrete wall, extending the entire height of the building at each facade in the opposite corner from the shaft would be a definite improvement. It would then be enough to construct two of the core walls in reinforced concrete and the rest could be for example in masonry (Switzerland 1994).

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6/2 This office building had a continuous fire wall to the right rear as well as more eccentric bracing at the back. The building twisted significantly, and the front columns failed (Kobe, Japan 1995).





6/3 6/4 In the back, this house share a strong and stiff fire wall with another house. In the front, the facade is substantially softer, so that the centres of resistance and stiffness were situated to the back of the building. The house twisted strongly in the horizontal plane, but did not collapse (Umbria, Italy 1997).

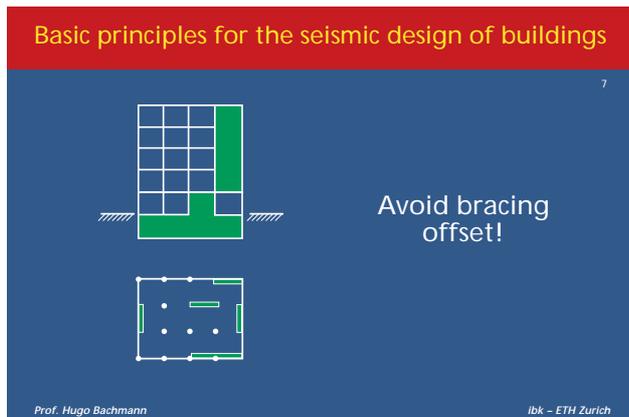


6/5 Originally, the only horizontal bracing in this 70's auditorium building at the Hönggerberg Campus of ETH Zurich were reinforced concrete walls with little torsional resistance situated at the rear of building. Because of the considerable distance between the bracing and the centre of mass of this large building, it would have twisted significantly in the plan for even a relatively weak earthquake (seismic zone 1 according to SIA 160). The few highly loaded reinforced concrete columns in the ground floor would have experienced substantial displacements, particularly in the front of the building. However, the column detailing was inadequate for the required ductility. Additional steel columns were therefore built in on three sides of the building exterior. They form a truss that can transfer the horizontal seismic forces to the existing foundations. This upgrading also fulfilled the need for a strengthening of the cantilevered structure for gravity loads.



6/6 The incorporation of the new tubular steel truss columns is aesthetically satisfying.

BP 7 Avoid bracing offsets!



Horizontal bracing offsets, in plane (at the bottom of the plan figure) or out of plane (at the top of the plan figure), result when the position of the bracing changes from one storey to another. The bending moments and the shear forces induced by the offset cannot be fully compensated, despite substantial additional costs.

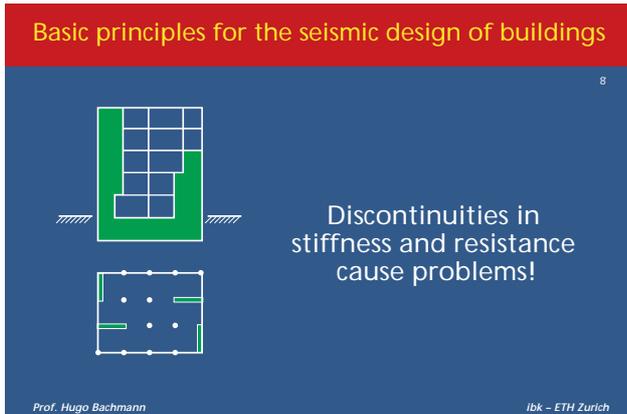
The offsets disturb the direct flow of forces, weaken the resistance and reduce the ductility (plastic deformation capacity) of the bracing. Moreover, they cause large additional forces and deformations in other structural elements (e.g. slabs and columns).

Compared to bracings that are continuous over the height of the building, bracings with offsets increase the vulnerability of the construction and usually noticeably reduce its seismic resistance. Bracing offsets must therefore be absolutely avoided!



7/1 The horizontal offset of the reinforced concrete wall in the vertical plane causes large additional stresses and deformations in the structure during an earthquake. They include large local vertical forces (from the overturning moment), large additional shear forces in the slabs at offsets, redistribution of the foundation forces, etc. (Switzerland 2001).

BP 8 Discontinuities in stiffness and resistance cause problems!



Modifications in the cross section of bracing systems over the height of a building cause discontinuities and lead to sudden variations in the stiffness and resistance of the building. This can cause irregularities in the dynamic behaviour and disturb the local flow of forces. An increase in the stiffness and resistance from the bottom up (left in the elevation figure) is generally less favourable than the opposite (right in the elevation figure). In any case, the calculation of the sectional forces and the design of the structure as well as the detailing of the discontinuities must be conducted very carefully.

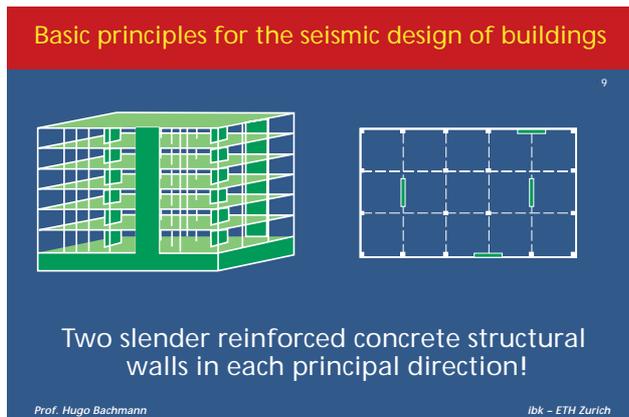


8/2 During an earthquake, the reinforced concrete cantilever wall (behind the curtain), will induce significant additional stresses in the already highly loaded column on the ground floor (Switzerland 2001).



8/1 The transition from a reinforced concrete structural wall to a frame structure causes large discontinuities in stiffness and resistance (Switzerland 2001).

BP 9 Two slender reinforced concrete structural walls in each principal direction !



9/1 Such reinforced concrete structural walls take up only little space in plan and elevation (Switzerland 1994).

Reinforced concrete structural walls of rectangular cross-section constitute the most suitable bracing system against seismic actions for skeleton structures. The walls may be relatively short in the horizontal direction – e.g. 3 to 6 m or about 1/3 to 1/5 of the building height – they must, however, extend over the entire height of the building. In a zone of moderate seismicity, in most cases two slender and capacity designed ductile walls in each major direction are sufficient. The type of non-structural elements can also influence the selection of the dimensions (stiffness) of the bracing system (cf. BP 14). To minimise the effects of torsion, the walls should be placed symmetrically with respect to the centre of mass and as close as possible to the edges of the building (cf. BP 6). Considering seismic forces transfer to the ground (foundation), corner walls should preferably be avoided. When the walls have L cross-section (angle walls) or U crosssections, the lack of symmetry can make detailing for ductility difficult. Reinforced concrete walls with rectangular cross-section (standard thickness 30 cm) can be made ductile with little effort, thus ensuring a high seismic safety [D0171].



9/2 The reinforcement of reinforced concrete structural walls is relatively simple, but it must be detailed and laid with great care. The figure shows a capacity designed ductile wall, of rectangular cross-section, which was added to an existing building (Switzerland 1999).

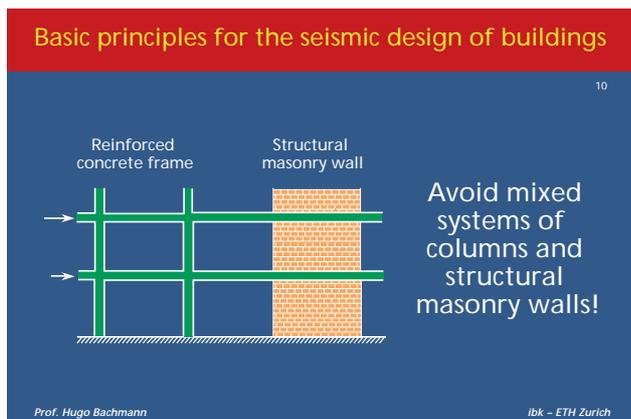


9/3 This skeleton structure has reinforced concrete structural walls in the transverse directions at two building corners.



9/4 The structural walls were included as prominent elements in the architectural concept (Switzerland 1994).

BP 10 Avoid mixed systems with columns and structural masonry walls!



Mixed structural systems with concrete or steel columns and structural masonry walls behave very unfavourably during earthquakes. The columns in combination with the slabs or beams form frames, which have a substantially smaller horizontal stiffness than the masonry walls. The earthquake actions are therefore carried to a large extent by the masonry walls. In addition to the inertia forces from their own influence zone, the walls must resist those from the parts of the building with the columns (to the left in the figure). This results in a seismic resistance considerably less than that of a «pure» masonry construction. When masonry walls fail due to the seismic actions or deflections, they can no longer carry the gravity loads, which usually leads to a total collapse of the building. Mixed systems of columns and structural masonry walls must therefore be absolutely avoided.

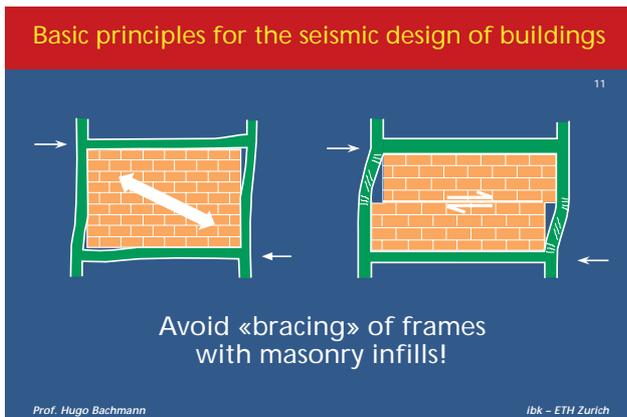
Furthermore, such mixed systems prove to be unfavourable because of their lack of flexibility with regard to increasingly frequent building modifications required by changes in their use. Removal of masonry walls require heavy structural interventions, which are costly (up to several percent of the building value) and

can impair the building functionally [D0171]. A consistent design of the structure as a skeleton structure, i.e. columns only (no masonry walls) with some slender reinforced concrete structural walls extending the entire height of the building, is thus also in the long-term interest of the owner. As the interior partitions are non-structural elements, they are easy to refit in case of changes in the building's use. Extensive structural modifications are therefore not necessary.



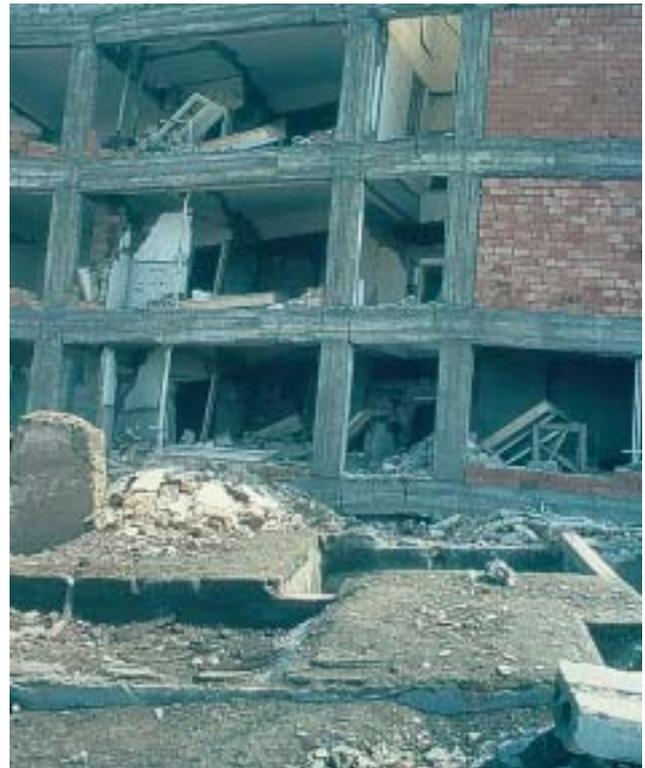
10/1 This structural stairway wall will be destroyed by a relatively weak earthquake. A total collapse of the building may result (Switzerland 2001).

BP 11 Avoid «bracing» of frames with masonry infills!



It is still a common opinion that filling in frame structures with masonry walls improves the behaviour under horizontal loads including seismic actions. This is true only for small loads, and as long as the masonry remains largely intact. The combination of two very different and incompatible construction types performs poorly during earthquakes. The frame structure is relatively flexible and somewhat ductile, while unreinforced masonry is very stiff and fragile and may «explode» under the effect of only small deformations. At the beginning of an earthquake the masonry carries most of the earthquake actions but as the shaking intensifies the masonry fails due to shear or sliding (friction is usually small due to the lack of vertical loads). The appearance of diagonal cracks is characteristic of a seismic failure.

Two basic cases can be identified: Either the columns are stronger than the masonry, or vice-versa. With stronger columns the masonry is completely destroyed and falls out. With weaker columns the masonry can damage and shear the columns, which often leads to collapse (see also BP 16 and 17).



11/1 Here the columns were clearly stronger and the masonry fell out while the frame remained standing (Erzincan, Turkey 1992).

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11/2 In this case the masonry was stronger: The columns experienced significant damage and were partly sheared; nevertheless, the frame is still just standing (Mexico 1985).



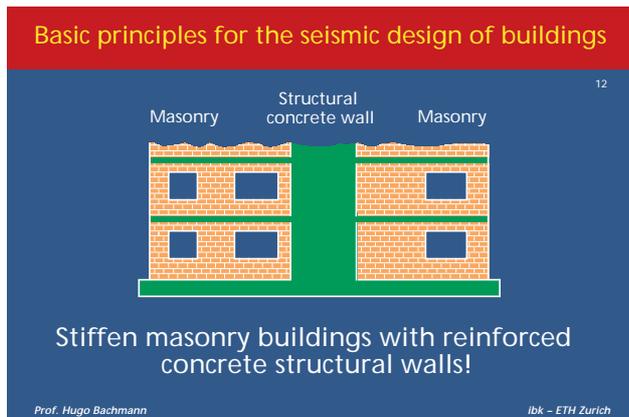


11/3 The masonry was also stronger in this case; it sheared the relatively large columns (Adana-Ceyhan, Turkey 1998).



11/4 These diagonal cracks are typical of reinforced concrete frame masonry infills (Turkey, Izmit 1999).

BP 12 Brace masonry buildings with reinforced concrete structural walls!



12/1 Such – and also lower! – new masonry structures, without bracing reinforced concrete structural walls, are extremely vulnerable to earthquakes (Switzerland 2001).

Traditionally in many countries, houses and smaller commercial buildings are often built with unreinforced masonry walls made of clay, limestone or cement bricks. Masonry is a good construction material in terms of thermal insulation, storage and vertical loads carrying capacity. For seismic actions however, masonry structures are not well suited. On one hand they are relatively stiff, so they usually have a high natural frequency – within the plateau area of the design response spectrum – and therefore experience large earthquake actions. On the other hand unreinforced masonry walls are rather brittle and generally exhibit relatively little energy dissipation. Generally, it is not possible to obtain adequate seismic resistance (even in regions of low seismicity) and additional measures are therefore necessary.



12/2 This new 3-storey residential building with unreinforced masonry structural walls is braced longitudinally by a reinforced concrete structural wall in each facade, and transversely by an interior reinforced concrete structural wall (Switzerland 2001).

A possible solution consists of bracing unreinforced masonry buildings with reinforced concrete structural walls. Hereby it is possible to limit the horizontal deformations of the masonry and therefore preserve its gravity load carrying capacity. The reinforced concrete structural walls must be designed to be sufficiently stiff, the horizontal wall length and the vertical reinforcement ratio being key parameters. They must be able to carry the seismic actions and to transmit them to the foundations while remaining elastic, i.e. without notable yielding of the reinforcement. The horizontal deflection of the reinforced concrete structural walls under the design earthquake must not exceed the displacement capacity of the stiffest, i.e. longest, masonry wall.



12/3 This new 4-storey masonry structure is braced by one reinforced concrete structural wall in each major direction. There is also a long masonry wall in both directions that has a horizontal layer joint reinforcement and is anchored to the concrete wall (Switzerland 2001).

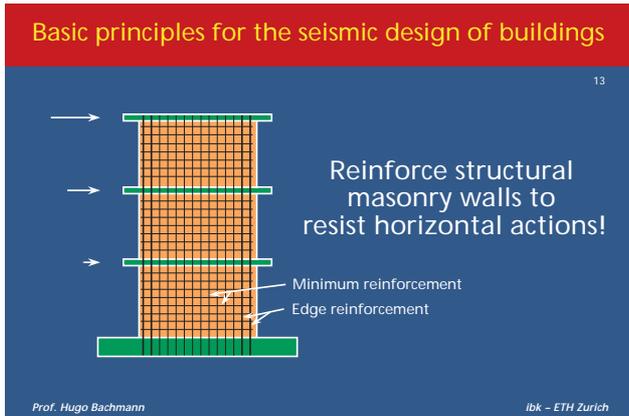


12/4 Structural masonry walls, reinforced concrete structural walls and slabs should respond together when subjected to shear, compression, and if possible tension (Switzerland 2001).



12/5 This is why it is recommended to fill in the joints between structural masonry walls and reinforced concrete structural walls with mortar (Switzerland 2001).

BP 13 Reinforce structural masonry walls to resist horizontal actions!



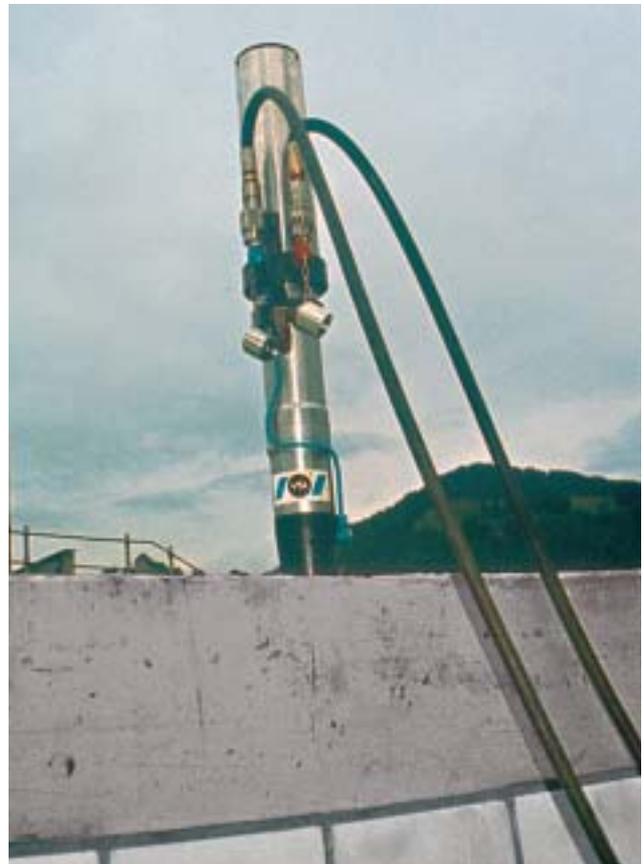
A possible alternative to basic principle 12 for making masonry structures substantially more suitable for seismic actions is to reinforce some long masonry walls and thus stiffen them in the longitudinal direction. In this case, for example, vertical and horizontal minimum reinforcement and stronger vertical reinforcement in the boundary zones must be detailed [Ba 02]. Thus sliding in the horizontal layer joints can be prevented and a global ductility of up to $\mu_{\Delta} \approx 2$ can be achieved. The reinforced walls can therefore be considered as «structural masonry walls for horizontal actions». The horizontal displacement of the reinforced masonry walls for the design earthquake must not exceed the ultimate displacement capacity of the stiffest i.e. longest, unreinforced masonry wall. This is necessary to ensure that the vertical load-bearing capacity of the unreinforced masonry walls is preserved.



13/1 13/2 Reinforced masonry requires special bricks, particularly to incorporate and coat the vertical reinforcing bars. Worldwide developments in reinforcing systems and adequate bricks are under way. The two pictures show new developments in the clay masonry industry (Switzerland 1998).



13/3 This type of vertical reinforcement is anchored at the top and bottom with U-shaped bars extending in 2 brick layers. The bars used to anchor the walls to the slabs or lower walls are very important (Switzerland 1998).



13/4 13/5 Vertical pre-stressing can also improve the earthquake behavior of masonry walls by substantially increasing the vertical force (Switzerland 1996).



13/6 The strength and ductility of masonry walls in existing buildings can be improved with carbon fiber or steel plate reinforcements (Switzerland 1996).



13/7 The plates must be glued on carefully and anchored in the slabs (Switzerland 1997).

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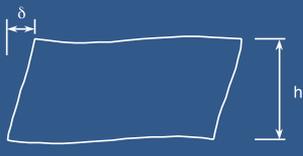
13/8 It is also necessary to consider the capacity requirement perpendicular to the wall («out-of-plane»). This applies in particular to gable walls (cantilever), to other masonry walls that are poorly restrained against horizontal forces and, for stronger earthquakes, also to walls supporting slabs. Here the walls in the upper floor, which carried only a small vertical load, failed «out-of-plane» (Loma Prieta 1989). Reinforcement, vertical pre-stressing, or glued on plates can also prevent such failure.



BP 14 Match structural and non-structural elements!

Basic principles for the seismic design of buildings

14



Governing size:
Inter-storey
displacement δ/h

Match structural and
non-structural elements!

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14/1 Here, the non-structural partition walls were destroyed, although the frame structure deformed only little and is hardly damaged. Even the windows remained intact (Armenia 1988).

If deformation-sensitive non-structural partition walls and facade elements (e.g. of masonry) are incorporated into a horizontally soft structure (e.g. a frame structure) without using joints, substantial damage may develop even for relatively weak earthquakes. Experience shows that in such cases a building must sometimes be demolished, even though the structure suffered no substantial damage. A modern earthquake resistant design must therefore match the stiffness of the structure and the deformation capacity of the non-structural partition walls and facade elements. The interstorey drift ratio (i.e. the interstorey drift, δ , divided by the interstorey height, h) and the vulnerability of the non-structural elements are crucial. The skillful selection and combination of structural and non-structural elements can prevent damages, even for relatively strong earthquakes.



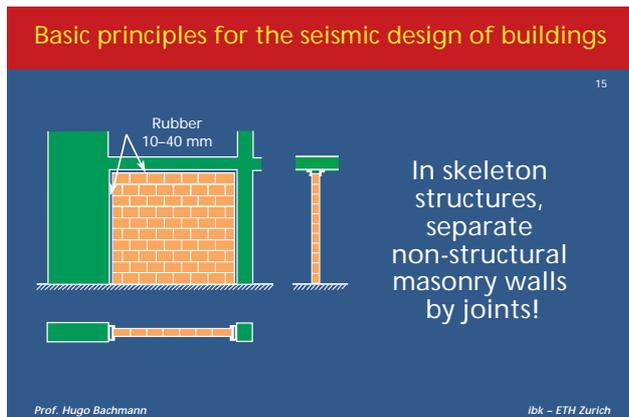
14/2 And here, a collapsed partition wall is simply rebuilt – until the next earthquake... (Adana-Ceyhan, Turkey 1998).

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14/3 The glass facade of this new multistorey building survived a strong earthquake almost without loss, owing to special flexible fastenings for the facade elements (Kobe, Japan 1995).



BP 15 In skeleton structures, separate non-structural masonry walls by joints!



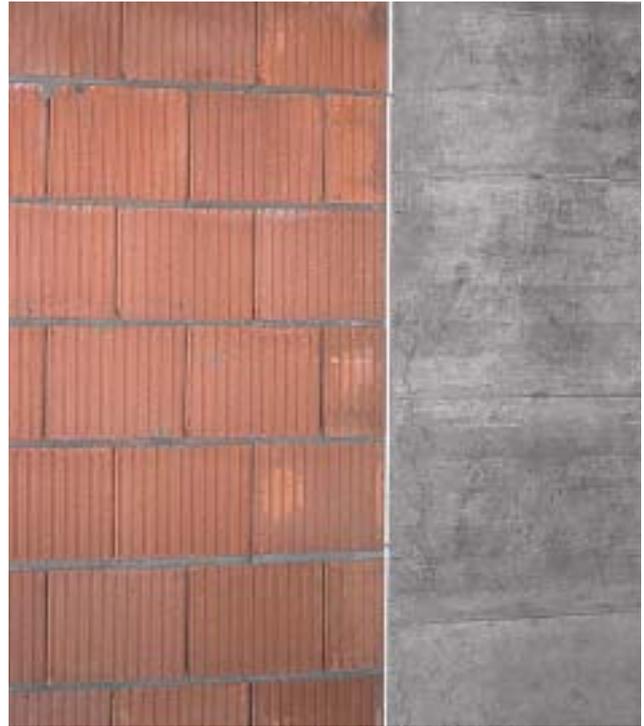
In flexible skeleton structures, it can be beneficial to separate non-structural partition walls from the structure by soft joints. This is particularly true for inplane stiff and brittle masonry walls. This way, damage occurring even for weak earthquakes can be prevented. The joints run along columns, structural walls, and slabs, or beams and must be filled by a very flexible soundproof material, e.g. boards of soft rubber. Styrofoam, cork, etc. are too stiff in this case. The necessary joint thickness (typically 20 to 40 mm) depends on the stiffness of the structure and the deformation sensitivity of the partition walls as well as the desired protection level (damage limit state earthquake < design earthquake) [D0171]. Generally the partition walls must also be secured against out-of-plane actions (plate effect), e.g. by support angles.



15/1 Here a vertical joint separates the masonry wall and the reinforced concrete column, but it is probably much too thin (Switzerland 1994).

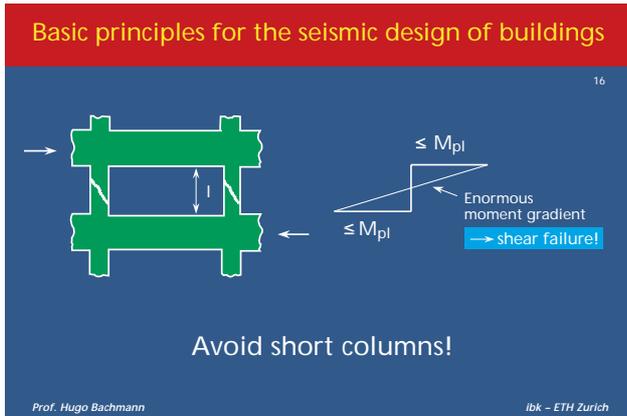


15/2 The joints thickness – here a horizontal joint between a masonry wall and a slab – and the capacity of the support angles (bolts) must be matched to the deformation of the structure and the capacity demand for the desired protection level (damage limit state earthquake) (Switzerland 1994).



15/3 This joint between a masonry wall and a reinforced concrete structural wall was filled by expanded polystyrene boards. But Styrofoam is too stiff for earthquake displacements; soft rubber would be a more suitable material (Switzerland 1994).

BP 16 Avoid short columns!



The shear failure of so-called «short columns» is a frequent cause of collapse during earthquakes. It concerns squat columns, i.e. columns that are relatively thick compared to their height, and are often fixed in strong beams or slabs. Slender columns can be turned into short columns by the addition of parapet infills in frame structures («unintentionally shortened columns»).

Columns under horizontal actions in frame structures may be stressed up to their plastic moment capacity (plastification or failure moment). In the case of short columns with considerable bending capacity, an enormous moment gradient and thus a large shear force results. This often leads to a shear failure before reaching the plastic moment capacity. Short columns should therefore be avoided. An alternative is to design and detail the columns in accordance with the rules of capacity design, whereby the shear capacity must be increased to account for the overstrength of the vertical reinforcement [Ba 02] [PP 92].



16/1 The diagonal cracks and shear failures in the short columns of a multi-storey car park almost caused collapse (Northridge, California 1994).

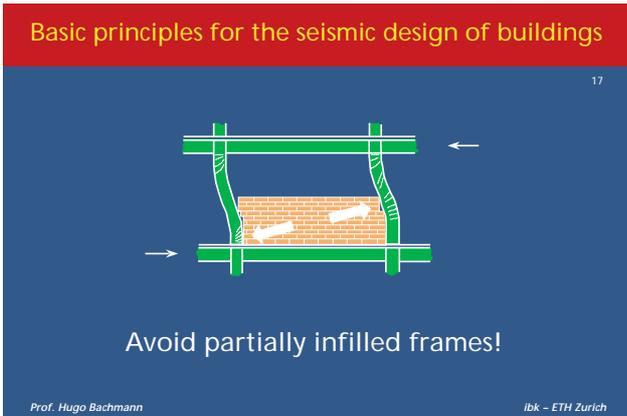


16/2 Here, the masonry columns in the ground floor of a restaurant behaved as short columns. They were highly damaged by diagonal cracks (Umbria, Italy 1997).



16/3 Shear failure in the corner short column on the ground floor led to near-failure of this commercial building (Erzican Turkey 1992).

BP 17 Avoid partially infilled frames!



The infill of parapet walls into a frame structure without the addition of joints can cause short column phenomena (see previous basic principle). Shear failure occurs, or – in cases of sufficient shear strength – a sway mechanism develops with possibly significant second order effects (P- Δ -Effect).



17/1 In this case, inserting parapet walls into a frame led to a short column phenomenon. Owing to the good confinement of the transverse reinforcement, no actual shear failure occurred, but an equally dangerous sway mechanism developed (Friaul, Italy 1976).



17/2 To the left of the destroyed column there used to be a window opening similar to the one on the far left of the picture. The already demolished masonry wall under the window opening behaved like a partial infill wall. It moved to the right, pushed against the column and sheared it off.



17/3 Better transverse reinforcement in the column (small spaced hoops and ties) would probably have prevented the shear failure. However, the source of the problem lies in the partial infilling of the frame that caused the short column phenomenon (Izmit, Turkey 1999).



17/4 Here too, inserting masonry walls and long window openings caused high additional stresses and column failure. The relatively good behavior of the massive column to the right in the picture contributed to the fact that the building narrowly escaped collapse.

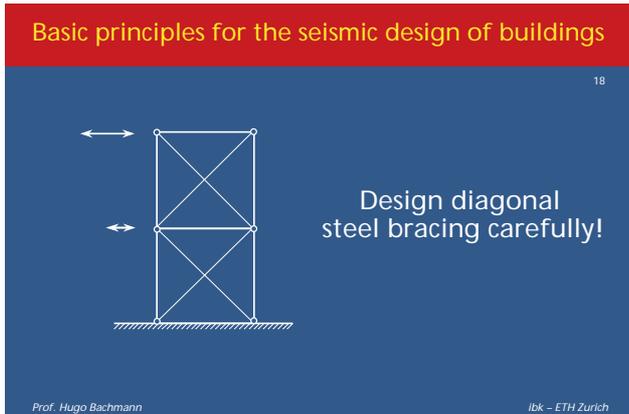


17/6 A possibility to avoid or strongly reduce the unfavourable effect of infill parapet walls into frames, is the addition of joints between the infill wall and columns. The joint was realized correctly, since it is filled by a soft and therefore strongly compactible rock wool sheet. However, the width only permits a 1% free lateral drift ratio of the column (Switzerland 2001).



17/5 This column illustrates unsatisfactory detailing (hoops with 90° instead of 135° hooks, compare with BP 25). Without the unfavorable effect of the infill walls it would however have behaved much better (Izmit, Turkey 1999).

BP 18 Design diagonal steel bracing carefully!



18/1 Diagonal elements with broad flange cross sections have buckled about their weak axis...

For the bracing of buildings, in particular industrial buildings, steel truss systems can be used. It must however, be carefully thought out and designed. The common truss bracing with centre connections and slender diagonal members may show a very unfavourable behavior under cyclic actions. The diagonals yield under tension, lengthen more with each cycle and end up buckling under compression. Under repeated cyclic movements, the stiffness of the truss becomes very small at the zero deformation point. This, combined with dynamic effects, can contribute to the failure of the structure. Such bracing must therefore only be designed for elastic behaviour, or if necessary very low ductility. It is advisable moreover to check compatibility between the deformations of the bracing and those of the other structural and non-structural elements. This can indicate the need for more stiff bracing or other bracing systems, such as walls. Steel truss systems with eccentric connections and compact members behave much better than trusses with centre connections and slender members [Ba 02].

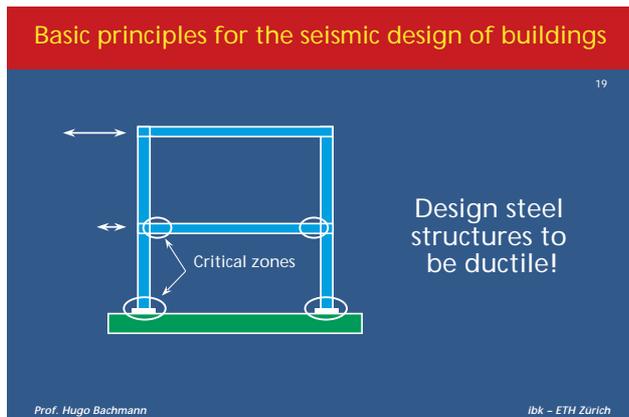


18/2 ... and have broken (Kobe, Japan 1995).



18/3 This truss structure also suffered buckling of truss elements and many local damages (Kobe, Japan, 1995).

BP 19 Design steel structures to be ductile!



Steel generally possesses a good plastic deformation capacity (strain ductility). Nevertheless steel members and steel structures may show low ductility or even brittle behavior under cyclic actions, particularly due to local instabilities and failures. For example elements with broad flanges (columns and beams) may buckle in plastic zones or fail at welds. Therefore, certain requirements must be complied with and additional measures must be considered during the conceptual design of the structure and the selection of the members cross sections [Ba 02] [EC 8].



19/1 This steel frame suffered large permanent deformations. There was probably no lateral bracing and the connection detailing was inadequate for cyclic actions (Kobe, Japan 1995).



19/2 The bolts failed in this beam to column connection (Kobe, Japan 1995).



19/3 This picture shows the failure of a typical frame connection. The welding between the column and the beam failed, resulting in a wide crack (Kobe, Japan 1995).

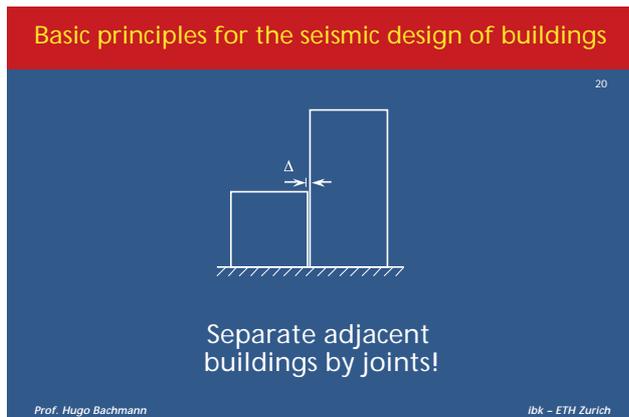


19/5 19/6 There is a wide crack at the bottom of this main frame column in a multi-storey steel building (to the right in the upper picture). Possible causes include the high cyclic normal loads, the high strain rate material defects, weld defects, and thermal stresses (Kobe, Japan 1995).



19/4 The rectangular column of this 3-storey frame structure suffered local buckling at its foot. The resulting cracking of the coating white paint is visible (Kobe, Japan 1995).

BP 20 Separate adjacent buildings by joints!



Pounding and hammering of adjacent buildings can cause substantial damage, if not collapse. The threat of collapse is greatest when the floor slabs of adjacent buildings are at different levels and hit against the columns of the neighbouring building. In such cases the joints must conform with the relevant design rules. This implies the following:

- 1) the joints must have a certain minimum width (specified in the building codes)
- 2) the joints must be empty (no contact points)

In order to enable free oscillations and avoid impact between adjacent buildings, it is often necessary to have a substantial joint width. As long as the structural elements do not lose their load bearing capacity at pounding, other solutions are also possible [EC 8].



20/1 The pounding of two similar buildings with floors at the same levels caused damage to the façades as well as spalling etc. to the structure (Mexico 1985).



20/2 Substantial damage resulted from the pounding of these two, very different, buildings (Mexico 1985).

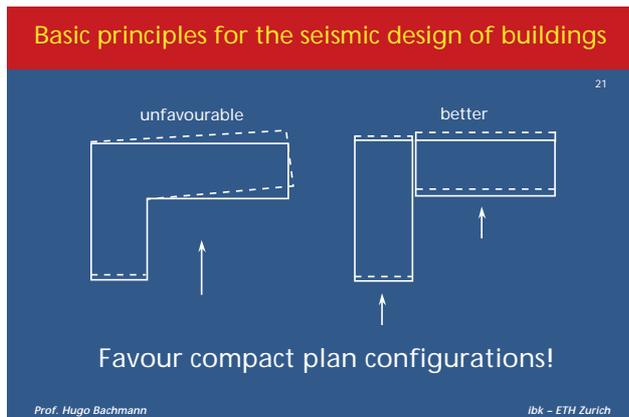


20/3 The modern reinforced concrete building to the left collapsed after pounding against the older very stiff building to the right (Mexico 1985).



20/4 The collapsed building was an extension of the older building to the left. Either the joint width was insufficient or the buildings were not connected properly. During the earthquake, the older building pounded against the new one and caused its collapse (Kobe, Japan 1995).

BP 21 Favour compact plan configurations!



When designing a building, it is important to visualise the dynamic behaviour of the structure as realistically as possible. In this L-shaped building, the stiffnesses of the two wings, respective to each principal direction, are very different. The two wings will tend to oscillate very differently but will also hinder each other. This leads to large additional stresses, particularly at the corners of the floor slabs and at the end of each wing, and may necessitate heavy structural measures. The problem can be avoided by separating the two wings by a joint respecting relevant seismic design rules. The result is two compact rectangular buildings that are «dynamically independent».

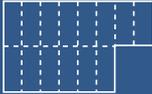
21/1 In order to allow building wings oriented orthogonally to each other to oscillate independently, they should be separated by a sufficiently wide and compressible joint.

BP 22 Use the slabs to «tie in» the elements and distribute the forces!

Basic principles for the seismic design of buildings

22

unfavourable



better



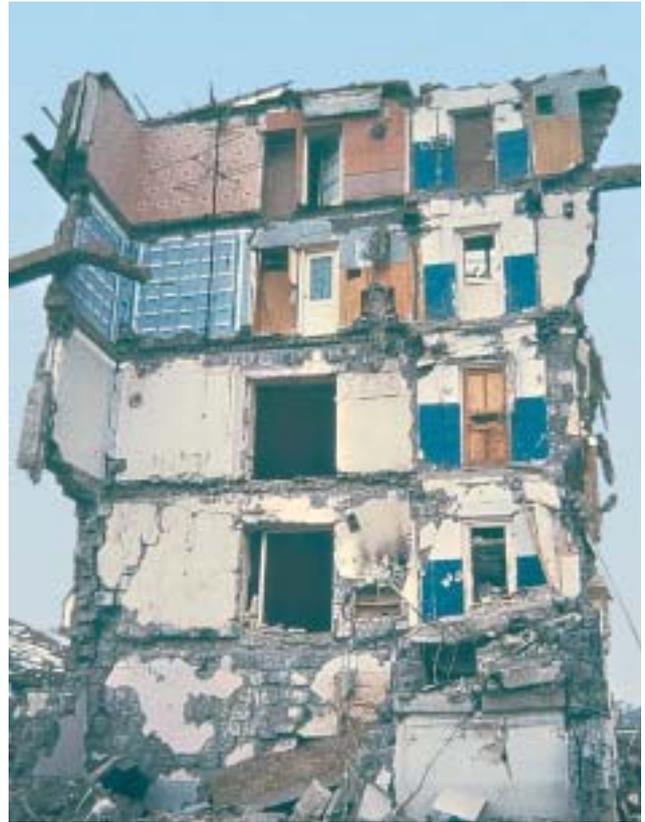
Use the slabs to «tie in» the elements and distribute the forces!

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In multi-storey buildings the floor slabs must be nearly rigid diaphragms. They must be properly connected to all the gravity load bearing elements to act as «section shape preservers» (diaphragms). The slabs have to ensure that all the vertical elements contribute to the lateral resistance. They distribute the seismic forces and displacements between the various vertical structural elements according to their individual stiffness. Slabs made of prefabricated elements are not recommended. If this solution is adopted, the floor elements must be covered with adequately cast in place reinforced concrete of sufficient thickness. Monolithic reinforced concrete slabs with eventual additional boundary reinforcement bars are much better suited to act as diaphragms.

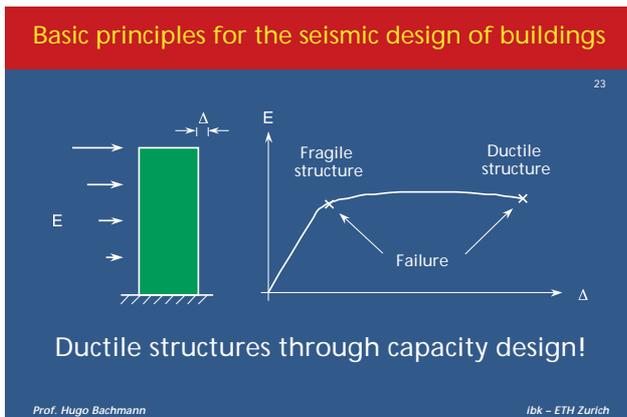


22/1 A corner area of this building collapsed. The slabs consisted only of precast elements without reinforced concrete cover and without reinforced connections to the vertical load bearing elements (Armenia 1988).



22/2 22/3 In these houses also, the slabs consisted only of precast elements, which were insufficiently connected between each other and with the walls (Armenia 1988).

BP 23 Ductile structures through capacity design!



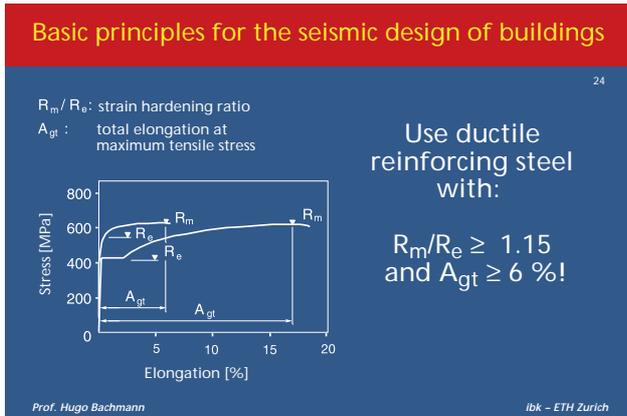
Ductile (i.e. with large inelastic deformation capacity) structures usually offer substantial advantages in comparison to similar brittle structures. Most importantly, the required structural resistance can be reduced bringing substantial savings and increased safety against collapse. Whenever possible the structure of a building should be designed to be ductile. This is also appropriate where the structural resistance for other reasons is so large that the design earthquake can be accommodated within the elastic capacity range of the structure. In this case, it is important because real earthquakes «do not read the codes» (T. Paulay) and may be substantially stronger than the design earthquake and bring the structure in its inelastic domain.

The capacity design method offers a simple and efficient approach to ductile structural design: The structure is «told» exactly where it can and should plastify, and where not. Hence, a favourable plastic mechanism is created. A large and predictable degree of protection against collapse can be achieved by good capacity design [PP 92] [Ba 02].



23/1 Static-cyclic tests on the lower part of 1:2 scale 6-storey reinforced concrete structural walls have clearly demonstrated the effectiveness of a ductile design [Da 99]. The capacity designed walls achieved, at little additional cost, a seismic capacity 3 to 4 times larger than that of walls conventionally designed according to the Swiss building code SIA 162.

BP 24 Use ductile reinforcing steel with $R_m/R_e \geq 1.15$ and $A_{gt} \geq 6\%$



In reinforced concrete structures the reinforcing steel must enable the development of sufficiently large and deformable plastic zones. Two parameters (ductility properties) are crucial to ensure this:

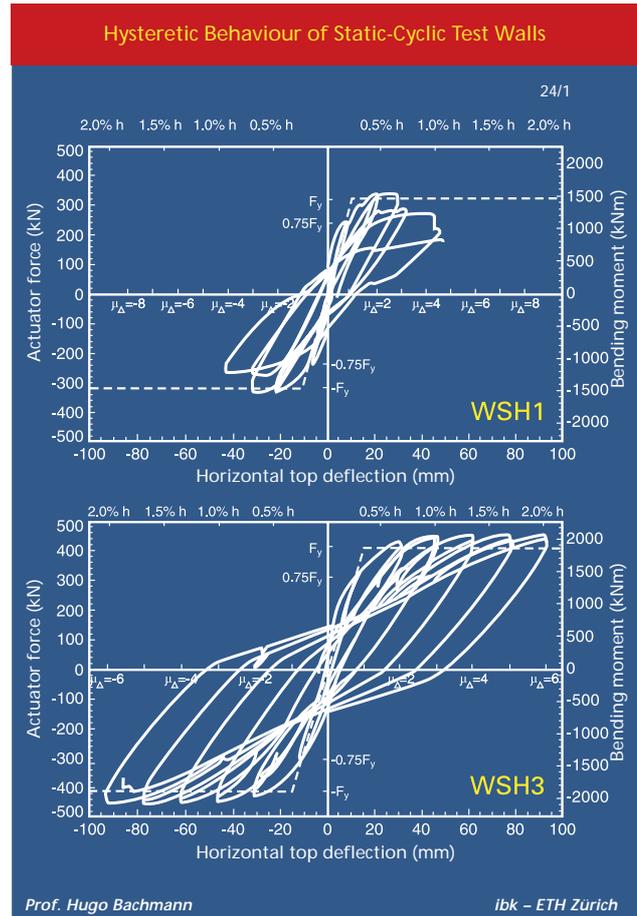
- strain hardening ratio R_m/R_e , i.e. the ratio between the maximum tensile stress R_m and the yield stress R_e
- total elongation at maximum tensile stress A_{gt}

The strain hardening ratio is also very important for the buckling resistance of reinforcement bars in compression. The smaller R_m/R_e , the lower the buckling resistance [TD 01].

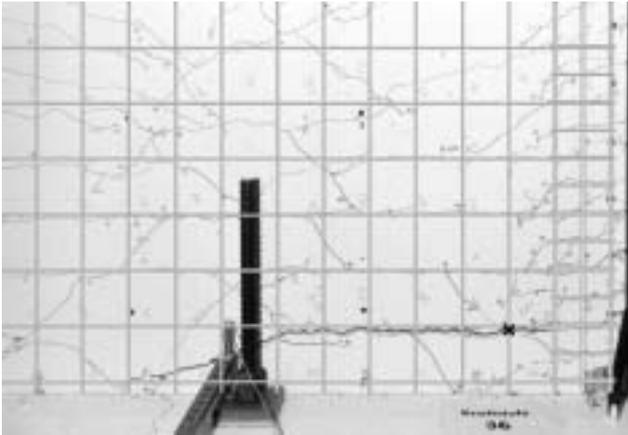
In Europe a large part of the reinforcing steel available on the market has insufficient ductility properties, in particular for the smaller bars with diameters up to 16 mm [BW98]. In order to ensure that reinforced concrete structures reach an «medium» ductility, it is necessary that the reinforcing steel fulfils the following minimum requirements (fractile values):

- $R_m/R_e \geq 1.15$
- $A_{gt} \geq 6\%$

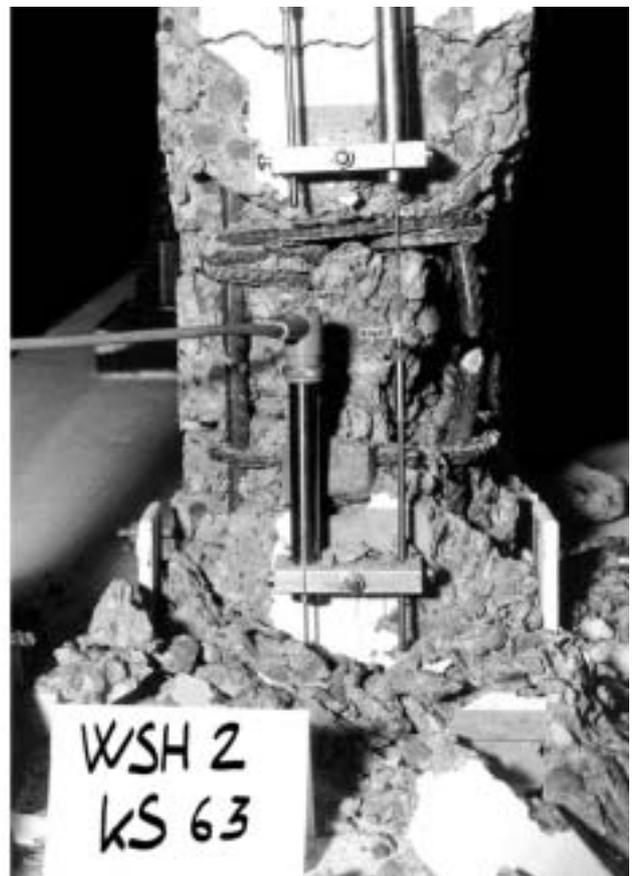
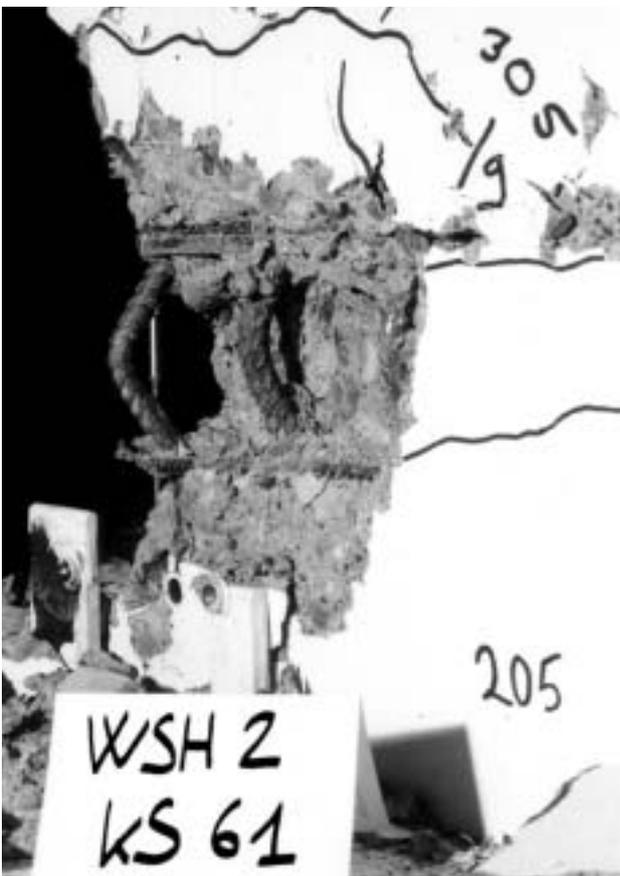
Designations such as «reinforcing steel in accordance with SIA building code 162» or «fulfils the building code requirements» or «ductile» or «very ductile» etc. are insufficient and misleading because the current building codes are themselves insufficient. It is therefore highly recommended that clear requirements are issued at the time of the invitation to tender and that suitable tests are made before the purchase and implementation of the reinforcing bars.



24/1 These plastic hysteresis-curves of 2 different 6-storey reinforced concrete structural walls with (WSH3) and without (WSH1) ductile reinforcing steel clearly illustrate the difference in behaviour. The wall with low ductility barely achieved a displacement ductility of $\mu_{\Delta} \approx 2$, while the ductile wall achieved $\mu_{\Delta} \approx 6$. The ductile wall can therefore survive an earthquake approximately 4 times stronger!

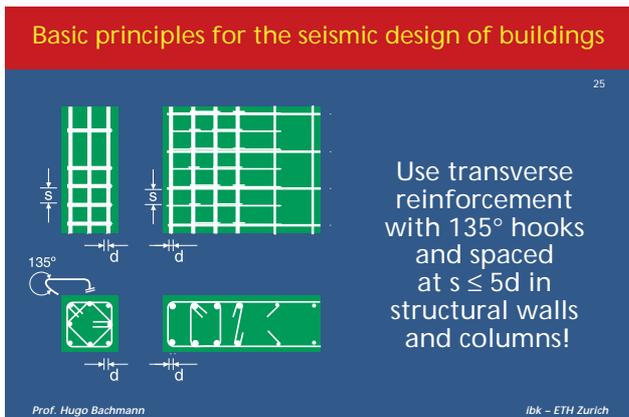


24/2 In this test wall, with reinforcement bars with insufficient strain hardening ratio R_m/R_e , the plastic deformations were concentrated at a single crack («one-crack hinge» according to [BW 98]). The reinforcement bars ruptured inside the wall (x) early in the test. This weakened the relevant section and concentrated the subsequent plastic deformations in it, causing the rupture of bars located at the edge of the wall. The wall barely reached a displacement ductility $\mu_{\Delta} \approx 2$ after 2 cycles [DW 99].



24/3 24/4 The failure of the reinforcement bars having a relatively low R_m/R_e value was initiated by their buckling in compression (left) followed after a load reversal, by rupture in tension (right). The rupture occurred where the reinforcement bars had experienced the largest buckling curvature [DW 99].

BP 25 Use transverse reinforcement with 135° hooks and spaced at $s \leq 5d$ in structural walls and columns!



Within cyclically stressed plastic zones of reinforced concrete structural walls and columns, the concrete cover spalls when the elastic limit of the reinforcement is exceeded. In these zones it is therefore necessary to stabilise the vertical bars against buckling and to confine the concrete to allow greater compressive strains. The stabilising and confining transverse reinforcement (hoops and ties) must be anchored with 135° hooks. Damaging earthquakes have repeatedly illustrated that 90° hooks are insufficient. The spacing of the transverse reinforcement must be relatively small $s \leq 5d$ (d = diameter of the stabilised bar). This is a consequence of the relatively poor ductility properties (small strain hardening ratio R_m/R_e) of European reinforcing steel, which result in an unfavourable buckling behaviour [TD 01].

Similar rules apply to the plastic zones in frame structures [Ba 02].

Within the zones that are to remain elastic according to the capacity design method it is sufficient to apply the conventional design rules.

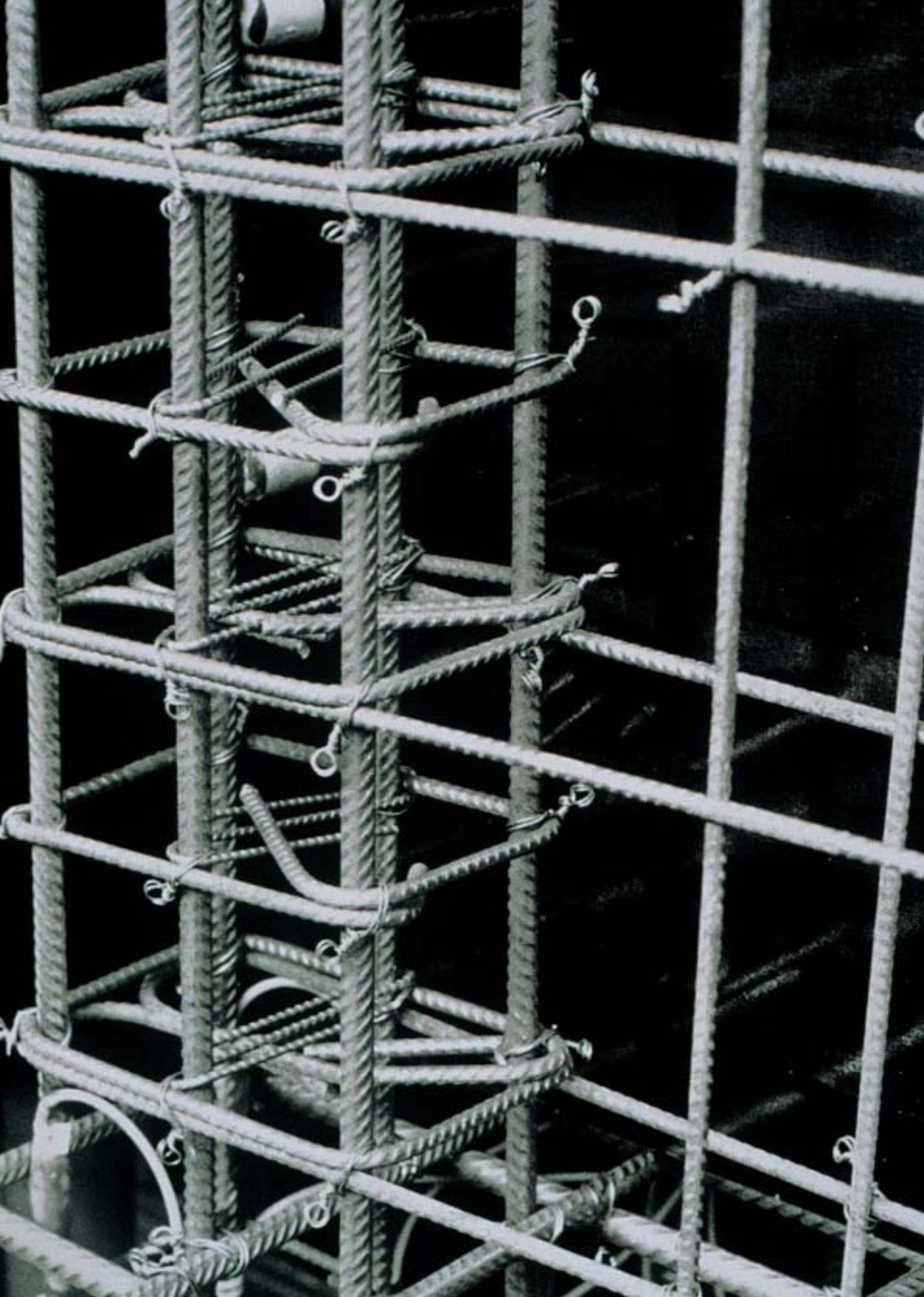
25/1 In this column of an industrial building made of precast reinforced concrete elements, the hoops were too widely spaced and insufficiently anchored with only 90° hooks. They consequently opened, allowing the vertical reinforcement to buckle (Adapazari, Turkey 1999).



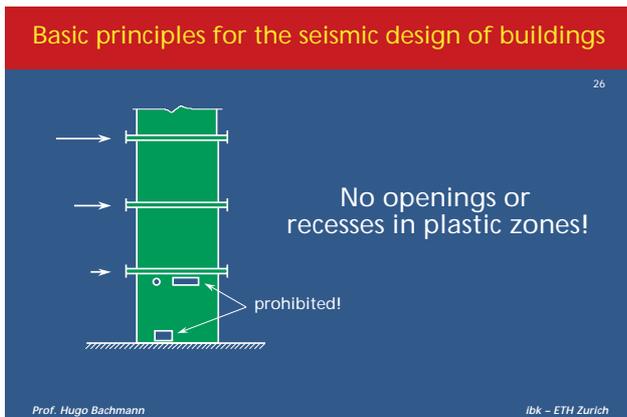
25/2 The hoops anchorage at the foot of this column in a frame structure also failed because the hoops only had 90° hooks (Turkey, Izmit 1999).

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25/3 This transverse reinforcement – hoops and ties – at the edge of a reinforced concrete structural wall is exemplary concerning anchorage with 135° hooks. However, the vertical spacing of the transverse reinforcement is too large, i.e. $s = 7.5d$ instead of $s \leq 5d$ as required for steel with a relatively small strain hardening ratio ($R_m/R_e = 1,15$) [DW 99][TD 01].



BP 26 No openings or recesses in plastic zones!



On some building sites there is a tendency to create recesses in the structure for services, air ducts etc., or even larger openings for other purposes, without consulting the civil engineer. These recesses and openings are often inserted into the formwork of reinforced concrete elements or even «jack hammered» after concreting. The repercussions are particularly serious when the openings are located in plastic zones. It is necessary to avoid this practice because it can lead to the premature failure of carefully designed «critical» structural elements and therefore to serious safety problems.

On the other hand, it is generally possible to place recesses and even larger openings in the elastic zones of the structure. The recesses and openings must be well planned and positioned, and the reinforcement around them must be strengthened eventually based on a frame calculation [D0171].



26/1 This well designed «earthquake wall» has been completely ruined by recesses placed in the formwork, careless creation of openings and brutal cutting of the reinforcement bars.



26/2 Expensive repair work, consisting of refilling the openings with expansive concrete and gluing steel plates restored the designed ultimate resistance of the wall. However, it is almost impossible to fully recover the ductile behaviour obtainable with the original reinforcement (Switzerland 2001).



26/3 Here, an excessively large hole was created and the reinforcement was brutally cut. Had the engineer been consulted the pipes could have been grouped and a much smaller hole could perhaps have been created without weakening the reinforcement.



26/4 However, it was possible to repair the damage to a certain extent and, in contrast to the preceding case (p. 60), to restore some of the planned behaviour (Switzerland 2001).

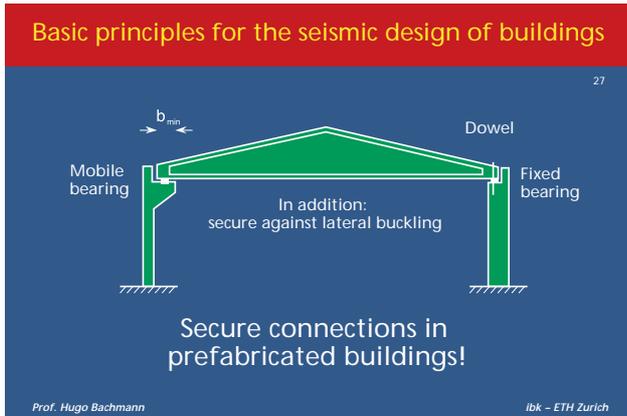


26/5 This type of unplanned insertion of pipes can also impair the seismic behaviour of a reinforced concrete structural wall (Switzerland 2001).



26/6 Under certain conditions, it is permissible to insert openings in elastic zones of «earthquake relevant» structural elements (here a slender reinforced concrete structural wall). Careful planning with the engineer is essential (Switzerland 2001).

BP 27 Secure connections in prefabricated buildings!



The connections in prefabricated buildings are often designed for construction gravity loads only. Such buildings can therefore be very vulnerable to earthquakes. Short support lengths, weak or missing dowels, and unsatisfactory overturning restraints of girders are frequently the cause of collapse. Therefore, mobile bearings must have a minimum support length (b_{min}) in accordance with the seismic building codes, and fixed bearings must have dowels designed for the forces accounting for the overstrength of the plastic zones (capacity design method). Additionally, the beams must usually be secured against lateral overturning movement. In case of prefabricated floors adequately reinforced concrete cast in place must cover and connect the floor elements in order to guarantee a diaphragm action (see also BP 22).



27/1 The dowels on the column corbels of this prefabricated factory building did not provide sufficient stability. The support area failed and the main beams overturned (in the direction of the longitudinal axis of the building)...



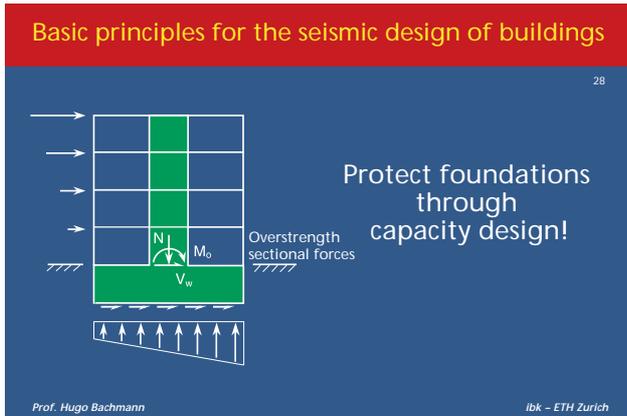
27/2 ... and the entire roof structure collapsed (Adana-Ceyhan, Turkey 1998).

Page 63

27/3 The consequences of bad planning and insufficient design and detailing of a prefabricated industrial building (Adapazari, Turkey 1999).



BP 28 Protect foundations through capacity design!



The ability of the foundation structure to bear the seismic actions is important for the overall earthquake resistance of the building. Usually, cantilever walls, as well as frame columns, rest on one or more basement storeys («rigid box») or on a massive raft. According to the principles of the capacity design method, the foundations should be able to transfer the overstrength sectional forces of the plastic zones to the ground without yielding [PB 90] [PP 92]. Foundation structures should always remain elastic since plastic deformations generally lead to an unpredictable behaviour and additional displacements and stresses in the building structure. Besides, repairs are usually substantially more difficult to execute in the foundation than in the building structure. The reinforcement must therefore be strengthened directly below the plastic zones and detailed accordingly [D0171].

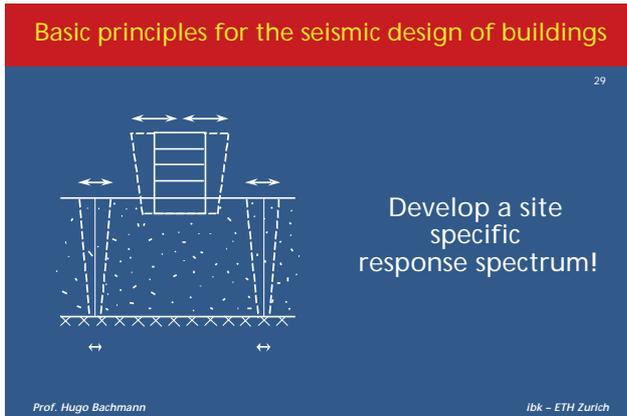
When the foundation structure forms a rigid box made up of reinforced concrete walls and slabs, it should be checked that the path of compression, shear, and tensile forces can be transferred from the plastic zones of the structural walls through the slabs to the exterior walls and to the raft. It may be necessary to reinforce these structural elements (accounting for possible recesses and openings) and to increase locally the depth of the raft and to account for a local increase in bearing pressure acting on the soil beneath the walls.

To ensure that seismic forces can be transferred to the soil it is advisable to study the force path in the foundation structure. The allowable soil stresses under dynamic action may be higher than the corresponding static stresses, but care should be taken to ensure that plastic deformations of the soil are avoided under all circumstances [SK 97].



28/1 Here soil anchors were installed to prevent the lift off of the ductile reinforced concrete shear walls (Switzerland 1999).

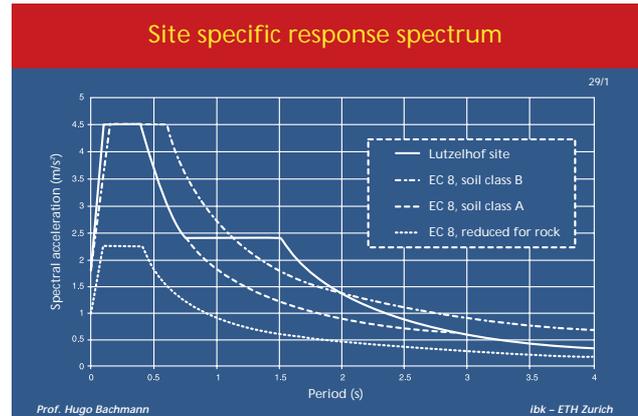
BP 29 Develop a site specific response spectrum!



In certain soils, the local ground motion parameters and structural response may differ substantially from the values obtained with the design response spectrum of the building codes. This can be the case:

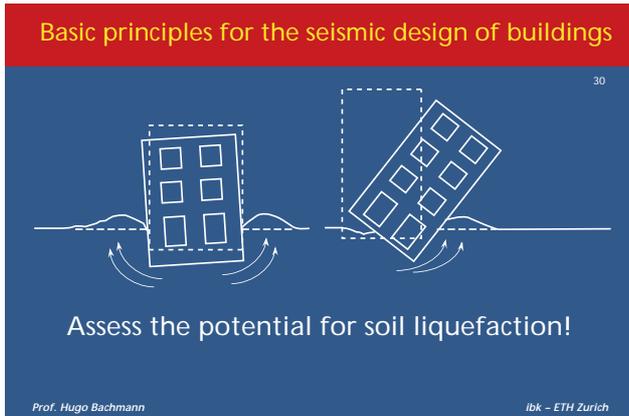
- in soft soils with a shear wave velocity less than approximately 200 m/s, and/or with large thicknesses of soil layers
- in certain valleys with alluvial or glacial sediments (depth to width ratio greater than ~ 0.2).
- generally in cases of suspected resonance between soil and building

Under such conditions, the ground is likely to experience strong vibrations even for a moderate earthquake (significant amplification of the ground shaking from the bedrock to the surface). In such cases, it is necessary to perform a site specific investigation, especially for important buildings. If no microzonation study has been conducted yet, it is necessary to determine the ground's predominant eigenfrequency and to develop the design response spectrum valid for the local soil's parameters and layer thicknesses (acceleration and displacement spectrum).



29/1 At the site of a building with planned «base isolation» (mounted on special earthquake bearings) the ground's predominant eigenfrequency measured in nearby drill holes was 0.65 to 0.85 Hz, which corresponds to an eigenperiod from 1.2 to 1.5 s. The development of a site specific response spectrum showed that the acceleration in this period range was substantially higher than that of the relevant building code spectrum. Hence this spectrum was raised and for a period greater than $T=1.5$ s a constant displacement was assumed. In order to eliminate the possibility of resonance and to minimize accelerations, a target eigenperiod of $T_0 \cong 3$ s ($f_0 \cong 0.33$ Hz) was selected in the seismic design with base isolators (Switzerland 2000).

BP 30 Assess the potential for soil liquefaction!



Certain sandy or silty soils saturated with water can display a sufficient static load-bearing capacity. However, when vibrated, such as during an earthquake, they will suddenly behave like a liquid. Entire buildings or sections thereof may sink, or tilt if the soil is inhomogeneous or unequally liquefied, often leading to total collapse. Sandy or silty soils must therefore be studied for their liquefaction potential. Counter measures such as consolidation by injections, pile foundations etc. can be necessary.



30/1 This building sank evenly about 1 m due to soil liquefaction. The displaced soil caused a bulge in the road (Izmit, Turkey 1999).



30/2 This inclined building sank unevenly and leans against a neighbouring building (Turkey, Izmit 1999).

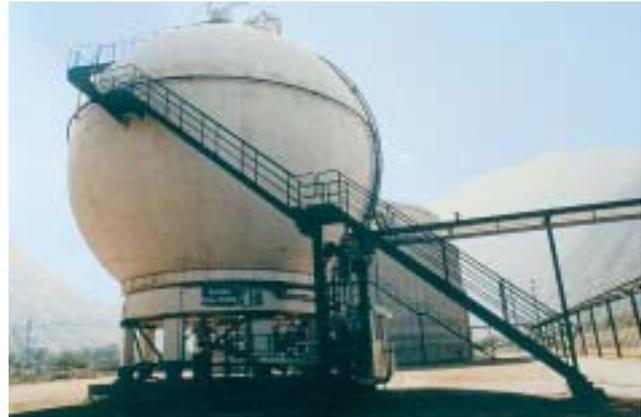
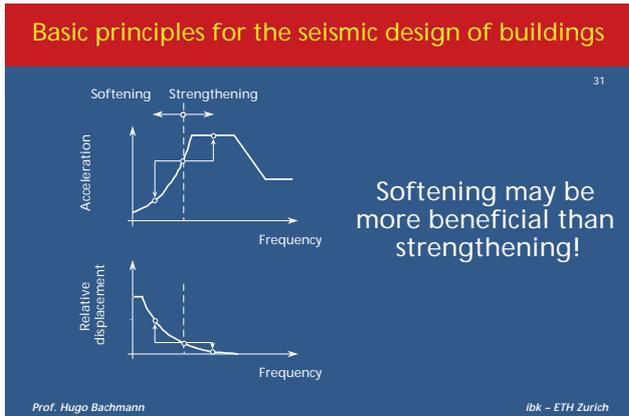


30/3 This solid building tilted as a rigid body and the raft foundation rises above ground. The building itself suffered only relatively minor damage (Adapazari, Turkey 1999).



30/4 This tank also tilted due to the liquefaction of the sandy artificial landfill (Kobe, Japan 1995).

BP 31 Softening may be more beneficial than strengthening!



When designing the seismic improvement of existing or planned buildings, many architects and civil engineers think of strengthening them, i.e. increasing their lateral resistance. A strengthening always stiffens the building, thereby raising the eigenfrequencies. Under certain conditions however, it may prove more beneficial to soften a structure rather than to strengthen/stiffen it [Ba 01]. By installing special horizontal relatively soft seismic bearings above the foundation (base isolation), a frequency shift towards the lower area of the design response spectrum can be achieved. As a result, and because damping is usually also increased, a significant reduction of the seismic forces and thereby the damage potential is achieved. However, relative displacements increase notably, which requires sufficient clearance around the isolated buildings. In addition service pipes must be sufficiently flexible.

31/1 A softening strategy was implemented to seismically improve this 700 t liquid gas industrial tank carried by a reinforced concrete structure (Switzerland 1999).

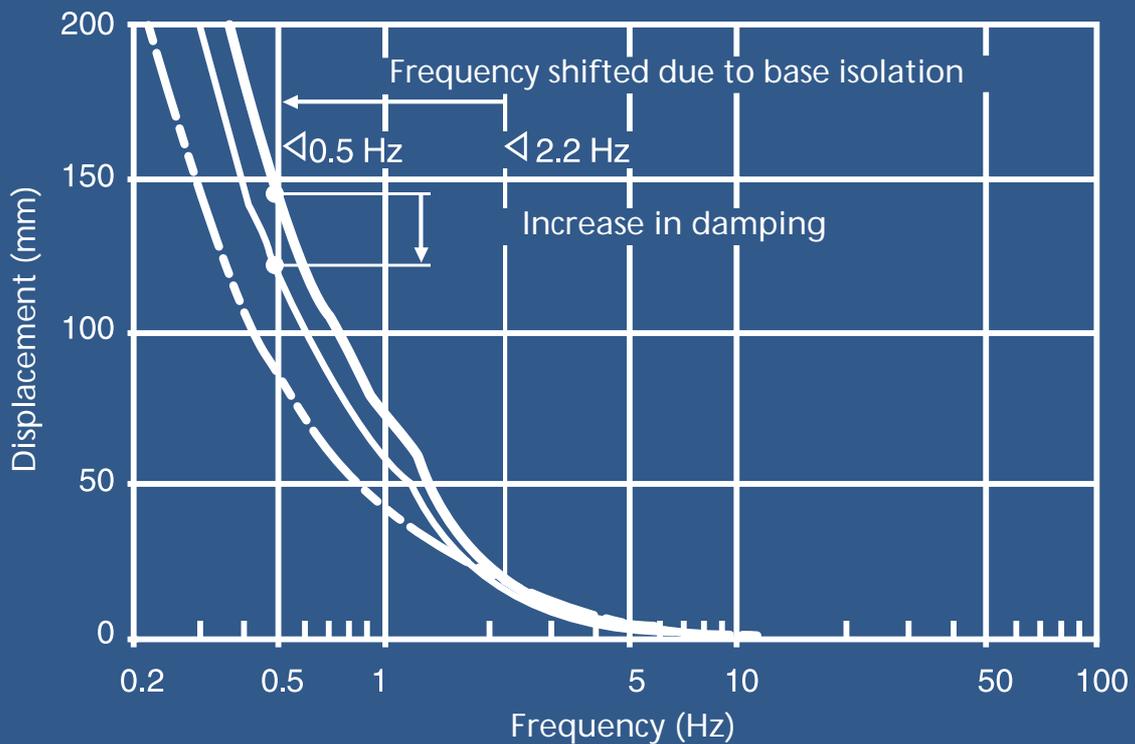
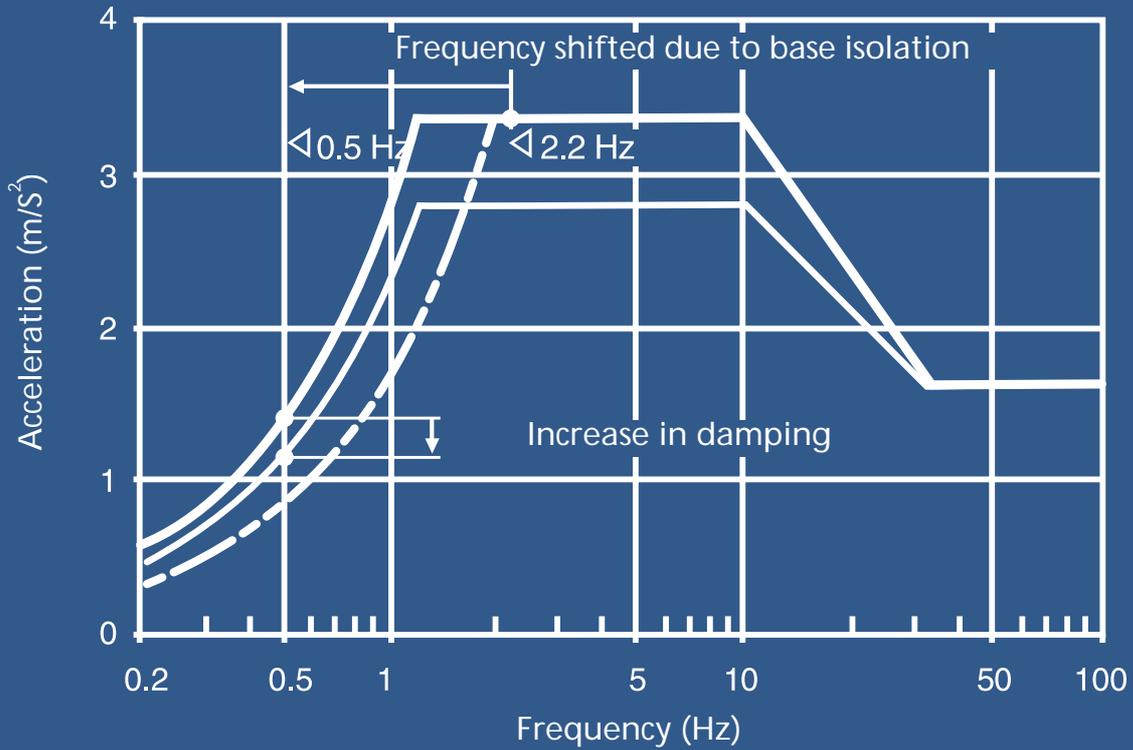


31/2 Seismic high damping rubber bearings (60 cm diameter, 30 cm high) were incorporated into the eight reinforced concrete columns.

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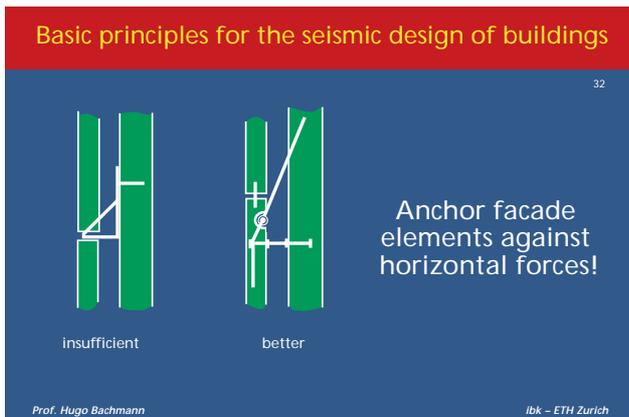
31/3 The acceleration and displacement design response spectra illustrate the combined effect of the reduction of the fundamental frequency to ~ 0.5 Hz and of the increase in damping.

Design spectra for industrial tank



- Site specific response spectrum $\zeta = 5\%$
- Site specific response spectrum $\zeta = 8\%$
- Spectrum for medium-stiff soil according to SIA 160 $\zeta = 5\%$

BP 32 Anchor facade elements against horizontal forces!



The facade elements anchoring is frequently designed for vertical gravity loads only. Often facade elements simply rest on corbels and are lightly fixed at the top. During earthquakes, the friction from the dead loads can be overcome by horizontal and vertical accelerations. The collapse of facade elements and the resulting threat to pedestrians, vehicles, etc. becomes inevitable. The facade elements anchoring must therefore be designed and detailed not only for gravity loads but also for horizontal cyclic forces (tension / compression). Additionally, the anchorages and possible connections between the facade elements should be able to follow the expected deformations of the structure.



32/1 The structure of this building did not collapse, but heavy and insufficiently anchored facade panels fell to the ground (Kobe, Japan 1995).



32/2 These light concrete panels, cladding an only slightly damaged steel structure, were also destroyed (Kobe, Japan 1995).

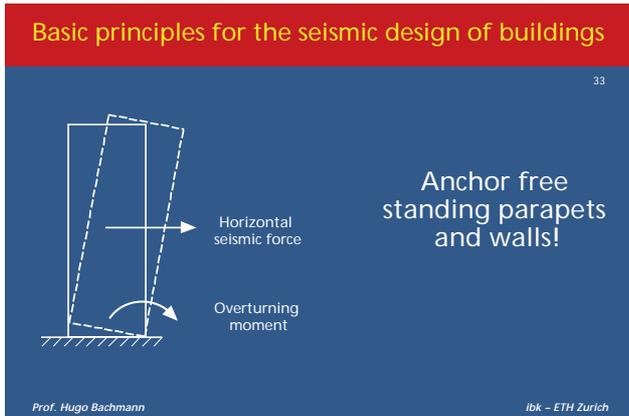


32/3 This facade cladding was insufficiently anchored and could not follow the deformations of the reinforced concrete frame structure (Northridge, California 1994).



32/4 A glance into this side street reveals a vast amount of fallen facade materials. Rescue work, fire trucks access, etc. is seriously hampered (Kobe, Japan 1995).

BP 33 Anchor free standing parapets and walls!



An overturning moment occurs under rapid horizontal displacements and corresponding inertia forces. Unless they are adequately anchored or fixed, slender elements may tip over.

33/2 ... and the cornice and parapet damaged the overhanging roof panel when they fell (Loma Prieta, California 1989).



33/1 This neo-classic reinforced concrete building did not suffer large damage and even the window-panes remained intact. However, the parapet on the roof terrace turned over...



33/3 Cantilever walls not anchored in the foundation can tip over (Kobe, Japan, 1995).

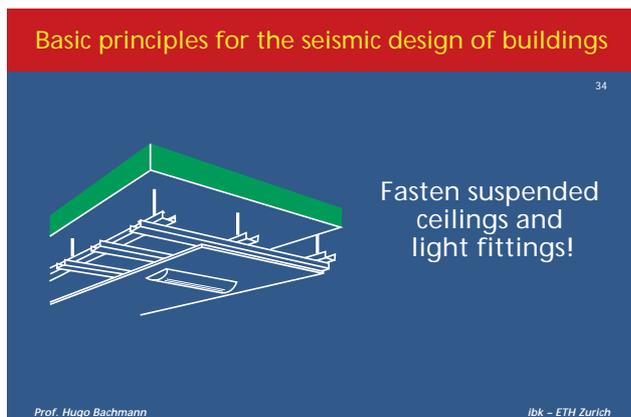
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33/4 These dry stone garden walls also turned over (Northridge, California, 1994).

SPEED
LIMIT
40

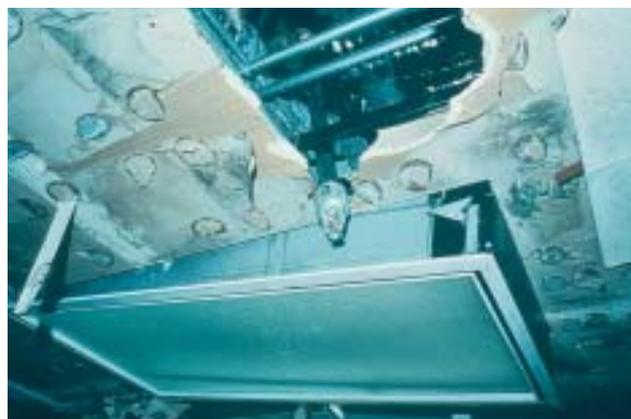


BP 34 Fasten suspended ceilings and light fittings!



34/2 ... that hang from thin wires only constitute a safety threat to people (Northridge, California 1994).

The fall of suspended ceilings and light fittings can present a serious danger to people. As well as the dead load, the connections must be able to safely carry the forces from vertical and horizontal accelerations and vibrations. The same applies to the fixings of air ducts and service pipes of all kinds, which are installed between suspended ceilings and structural floor slabs.

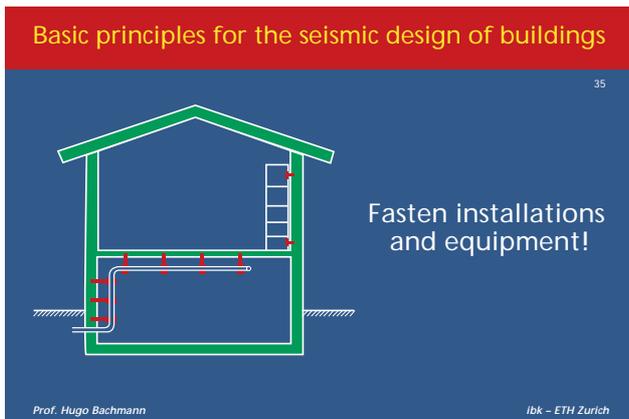


34/1 Suspended ceilings and ceiling panels...



34/3 34/4 Poorly fastened light fittings, such as these, can fall and endanger people (San Fernando, California 1971).

BP 35 Fasten installations and equipment!



It is very important to guarantee the integrity of installations and equipment that must remain operational after a strong earthquake, including equipment outside the building, on roofs etc. This concerns primarily «lifeline structures» which are vital for rescue operations and recovery (buildings of class III according to SIA 160), such as hospitals, main pharmacies, fire-fighting facilities, operational command centres, communication installations etc. It can also include industrial facilities whose business interruption would cause significant financial losses. All installations and equipments such as pipelines, water fire sprinklers, laboratory instruments, containers, cabinets, shelving units etc. and if necessary also production lines must be systematically examined for seismic adequacy. If necessary they must be secured by means of suitable fixings or bracings.



35/1 Pipelines – especially of large diameter – are very vulnerable unless they are adequately fastened (San Fernando, California 1971).



35/4 Filing cabinets can tip over, particularly if the drawers are not secured (Morgan Hill, California 1984).



35/6 Because books represent a considerable mass, strong anchorage and bracing of the shelves in both main directions is necessary (Whittier Narrows, California 1987).



35/5 Open bookshelves empty themselves at each strong earthquake. Valuable books can be secured by the use of retaining bars or inclined shelves (Loma Prieta, California 1989).



35/7 Well-secured battery groups and emergency power generators can guarantee a power supply, even after a strong earthquake (California 1980).



35/8 These «valuable» bottles in a liquor store were secured by spring wires (California 1978).



35/9 And even storage frames for wine barrels can be tested on an earthquake simulator (shaking table)... (Berkeley 2000).

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Global Seismic Hazard MAP

Produced by the Global Seismic Hazard Assessment Program (GSHAP),
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