32
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> Seismic retrofitting of structures

Strategies and collection of examples in Switzerland

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> Table of Contents

> Abstracts

This publication provides a detailed insight in the problematic of the seismic retrofitting of existing structures. The presentation of 24 examples of seismic retrofitting projects in Switzerland illustrates the different possible strategies and gives suggestions and decision criteria on how to handle the complex problem of the seismic safety of existing structures. The publication is primarily aimed at structural engineers, but architects, building owners and homeowners will also find valuable information on the management of earthquake risk for existing structures.

Keywords:
Earthquakes, mitigation, existing structures, seismic retrofitting, collection of examples, strategy, Switzerland

Diese Publikation bietet einen vertieften Einblick in die Problematik der Erdbebenertüchtigung bestehender Bauwerke. Anhand von 24 Musterbeispielen ausgeführter Erdbebenertüchtigungsprojekte in der Schweiz werden mögliche Strategien anschaulich dargestellt sowie Anregungen und Entscheidungshilfen aufgezeigt, die zu einer optimalen Lösung dieser sehr anspruchsvollen Aufgabe führen sollen. Die Publikation richtet sich primär an in der Praxis tätige Bauingenieurinnen und -ingenieure, bietet aber auch für Architektinnen und Architekten, Bauherrinnen und -herren sowie Hauseigentümerinnen und -eigentümer wertvolle Informationen, wie mit dem Erdbebenrisiko bei bestehenden Bauwerken umgegangen werden kann.

Stichwörter:
Erdbeben, Vorsorge, bestehende Bauwerke, Erdbebenertüchtigung, Beispielsammlung, Strategie, Schweiz

Cette publication présente un aperçu détaillé de la problématique du confortement parasismique d'ouvrages existants. Les différentes stratégies possibles sont illustrées à l'aide de 24 exemples de projets réalisés en Suisse et des suggestions et des aides à la décision sont fournies pour savoir comment cette problématique très complexe peut être résolue de manière optimale. La publication s'adresse en premier lieu aux ingénieurs de la pratique, mais les architectes, les maîtres d'ouvrages et les propriétaires y trouvent également des informations utiles sur la gestion du risque sismique pour les ouvrages existants.

Mots-clés:
tremblements de terre, mitigation, ouvrages existants, confortement parasismique, recueil d'exemples, stratégie, Suisse

Questa pubblicazione offre un quadro dettagliato della problematica relativa al rafforzamento antisismico delle costruzioni esistenti. Con i suoi 24 esempi di progetti di rafforzamento antisismico realizzati in Svizzera, essa illustra le possibili strategie e fornisce consigli e supporti decisionali per la soluzione ottimale di questo problema complesso. La pubblicazione si rivolge in primo luogo agli ingegneri civili, ma anche gli architetti, i committenti e i proprietari di immobili possono trovarvi preziose informazioni su come gestire il rischio sismico delle costruzioni già esistenti.

Parole chiave:
Terremoti, mitigazione, costruzioni esistenti, progetti di risanamento, raccolta di esempi, strategia, Svizzera

> Foreword

Until 2004, in Switzerland there were neither a practical criteria for the assessment of seismic safety of existing structures nor a cost related description of the proportionality of retrofitting measures. This gap was closed with the support of the “Coordination Center for Earthquake Mitigation” of the Swiss Federal Office for the Environment (FOEN) when the new Pre-Standard SIA 2018 “Examination of seismic safety of existing structures with regards to earthquakes” was introduced. Since the publication of this Pre-Standard, the attention of the subject matter of seismic safety and seismic retrofitting of existing structures has clearly increased.

Since December 2000, that is since the program of the Swiss government for earthquake mitigation took effect, the Swiss government has been examining the seismic safety of existing structures in its area of responsibility. For existing structures with insufficient seismic safety, measures are systematically taken under the consideration of proportionality of costs. On the level of the cantons, the examinations for seismic safety of existing public buildings and engineering works in most of the cantons were institutionalised and are realised. The federal government and about half of the cantons have already completed seismic safety measures of their own structures, often by means of reconstruction or rehabilitation.

At present, very few cantons possess laws or ordinances in which earthquake resistant design of private buildings are explicitly embodied. In most cases the responsibility is left to the private building owner and the project’s responsible person to reach an agreement on the decision for an examination and for eventual retrofitting measures of the existing structure. In comparison to public structures, seismic retrofitting of existing private structures is still relatively rare.

With its program in the area of earthquake mitigation the federal government undertakes its part as role model and instigator and supports cantons, building professionals, insurance companies, and private individuals with methodical bases and expertise. With this publication the Federal Office for the Environment (FOEN) will pass on the collected experience in the area of seismically retrofitting existing structures in Switzerland and the resulting insight from it. The primary targeted groups are the building professionals in the area of planning and construction and building owners.

Andreas Götz
Vice Director
Federal Office for the Environment (FOEN)

> Introduction

This publication is primarily intended to address practicing structural engineers. With the help of instructive examples carried out on retrofitting projects throughout Switzerland, possible strategies for seismic retrofit as well as the stimuli and helpful decisions to optimally solve the demanding problem are clearly and illustratively described. Architects, building owners, and home owners will receive valuable information on how existing structures should be managed for earthquake risk, a major natural hazard in Switzerland.

In the first chapter, dealing with existing structures, the topics of seismic safety of existing structures, the reason for examination, and the risk-related basis of decisions for a retrofit according to Pre-Standard SIA 2018 "Examination of existing buildings with regards to earthquakes" are explained.

The second chapter is dedicated to the possible strategies for seismic retrofitting. Depending upon different boundary conditions, suitable strategies are described for the improvement of existing structures for earthquake safety.

The third and main chapter of the publication consists of a collection of examples of 24 existing structures in Switzerland, which were seismically retrofitted with structural measures during the last few years. Each structure is introduced on a short center fold with typical photographs and sketches of the essential conceptual and constructive aspects of the retrofit. In addition, the topics of *structural weakness referring to seismic behaviour of the initial state, retrofit plan, highlights,* and *context* are described. Finally, some of the characteristic relevant data such as the year of construction, building use, building value, importance class, seismic zone, ground type, compliance factor, and the cost of the retrofit are summarised in a table.

For the collection of examples, buildings were selected to be as different and extensive as possible according to building use, structure type, ground type, seismic zone, and retrofit plan. Besides buildings, examples of a highway bridge and a liquid gas tank were also included to give insight into particular aspects of different structures. Three buildings make up the end of the collection of examples, in which the existing state could be accepted as sufficiently earthquake-proof – a frequent result from the examination of existing structures in Switzerland.

Subject specific information such as the historical development of seismic regulations in the Standards and the retrofitting costs of the examples are summarised in the appendix.

1 > Dealing with existing structures

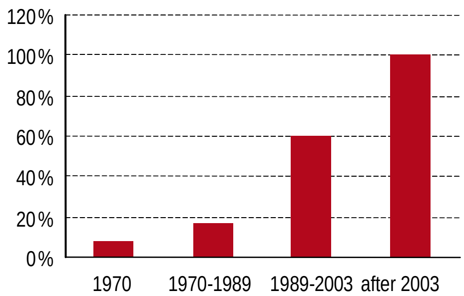
In recent years the seismic requirements in building standards have been getting distinctly more rigorous. Because of widespread disregard of these regulations, the question of seismic safety is not only for older buildings but also for newer ones. The result is a need for action not only on the public but also private level. To gain clarity over the necessity to perform a retrofit, existing buildings have to be examined with regards to earthquakes.

1.1 Seismic assessment of existing buidings in Switzerland

After the introduction in 1970 of the first seismic regulations in the building standards of the Swiss Society of Engineers and Architects (SIA) (Standard SIA 160 1970), the design requirements were strengthened in later standards in 1989 and 2003. The background for these changes was new knowledge in earthquake engineering and in seismology. Figure 1 shows the exemplary development of horizontal design forces since 1970 for earthquake and wind actions on 4-storey, multi-family houses made of masonry. A detailed description of the history of the development of seismic requirements is found in Appendix A1.

Fig. 1 > Development of horizontal design loads for typical residential buildings

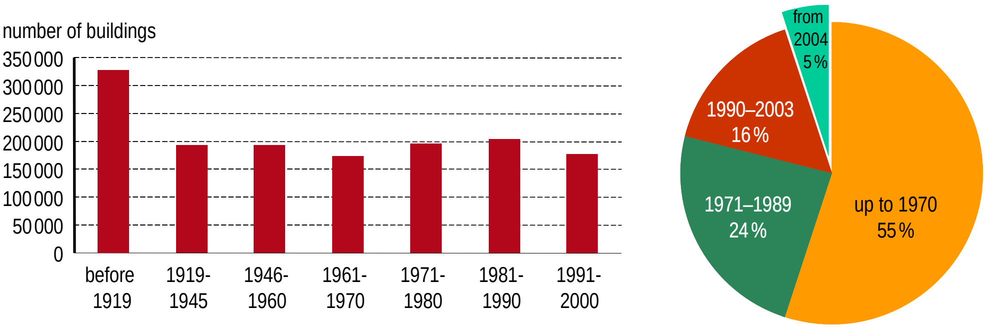
Relative size of the horizontal design forces in the longitudinal direction of 4-storey, multi-family houses made of masonry in the center plains of the country (seismic zone Z1). Before 1970, the design forces were due to wind affects, after 1970 that was changed to earthquakes.



Since 1970, the inventory of buildings in Switzerland has rarely been renewed. Figure 2 shows the distribution of existing buildings according to revisions of earthquake standards based on the data of the federal population census from the year 2000 (BFS 2004). Fifty-five percent of all buildings were built before the first earthquake regulations of Standard SIA 160 came into force (1970). Twenty-four percent fall in the time between 1971 and 1989. Only twenty-one percent were built since 1990 after today's view of modern earthquake standards. And only five percent of them were constructed according to today's valid standard of 2003. Nevertheless, as a consequence of an underestimation of earthquake risk and an insufficient legal obligation, the seismic provisions of the standards were often not obeyed.

Fig. 2 > Inventory of buildings in Switzerland

Distribution of building inventory after building period (left) and after revisions to SIA Standards (right).



Owing to constructional aspects and wind design, older buildings show a certain basic protection against earthquakes even though they were not designed for seismic actions. However, it must be said that referring to seismic behaviour, many older buildings and above all those with typical structural deficiencies do not fulfil the requirements of today's standards. The most important and in Switzerland the most frequently observed are **structural weaknesses** with negative consequences for seismic behaviour (see also Fig. 3).

> **Horizontal weak storey or "Soft-Storey"**
  Often the massive bracing of higher storeys, such as walls, are omitted in the ground floor level. The remaining columns in the ground floor level are not sufficient to carry seismic effects.
> **Unsymmetrical bracing**
  In plan, an unsymmetrically arranged bracing system creates additional torsion for the building under earthquakes. This can lead to early failures.
> **Masonry construction without reinforced concrete walls**
  Masonry construction is very common for residential buildings because of the ease of handling and the favorable physical quality. Because of its low tensile strength and its brittle nature, unreinforced masonry is less suitable under seismic effects.

Fig. 3 > Typical structural weaknesses referring to seismic behaviour

Building with horizontal weak ground floor (Example 5: residential and retail shop in Sion)	*Building with unsymmetrical bracing (Example 15: auditorium at ETH Zurich)*	*Building with unreinforced masonry (Example 7: school in Monthey)*

1.2 Reason for an examination of earthquake safety

Due to the repeated strengthening of the seismic regulations in the SIA structural standards during the last decades, existing structures should be examined independent of planned renovations or reconstructions. With a large building stock it is recommended to have a risk-based prioritisation.

1.2.1 Building use and structural classification

According to Standard SIA 261 "Action on Structures" (SIA 261 2003), buildings are divided into one of three **importance classes** (**IC**). The degree of protection referring to seismic safety is set with this division. Criteria for the choice of classification are the average occupancy, the potential for damage, the exposure of the environment to danger, and the importance of the structure in the emergency management immediately after an earthquake. Regular residential and commercial buildings are classified as IC I. Buildings with a higher occupancy level are in IC II, and so called essential facilities with important life-saving infrastructure functions, such as fire stations, ambulance garages or emergency hospitals, are in the highest classification of IC III. Figure 4 shows the typical building examples for the three importance classes.

1.2.2 Prioritisation

Important structures, that means IC II and especially IC III, should be systematically examined independent from the long term, general maintenance plan and, if necessary, retrofitted. This way the structures with the greatest potential for risk are caught and dealt with. For this purpose, step by step proceedures with increasing examination depth are recommended. Suitable filtering criteria allow to identify critical buildings and to establish at the same time a general inventory. The urgency and the extent of the examinations and retrofittings could then be planned by risk-based criteria (BWG 2005, BWG 2006). In the context of such systematic examination of building inventories, it is recommended to give highest priority to buildings in higher seismic hazard zones (seismic zones Z2, Z3a and Z3b according to Standard SIA 261) (see Appendix 1).

1.2.3 The potential for synergy in reconstruction and renovation

Whenever possible, measures for seismic retrofitting should be realised together with reconstruction and renovation to make use of synergies. The costs of the seismic retrofitting could be substantially reduced. When structural measures such as reconstruction or renovation are planned for a building, the examination for seismic safety should be included, such that necessary measures are identified early in the planning process.

Fig. 4 > Examples of the three importance classes according to Standard SIA 261

Importance class I (Example 25: residential house in Kriessern SG)

Importance class II (Example 13: school in Ostermundigen BE)

Importance class III (Example 3: fire station in Basel)

1.3 Examination of earthquake safety according to Pre-Standard SIA 2018

Whether an existing building satisfies today's seismic regulations in the SIA structural standards, it will be judged on the basis of an examination according to Pre-Standard SIA 2018 (2004) "Examination of existing buildings with regards to earthquakes". If the existing building does not fully satisfy today's seismic regulations, it does not automatically move to the obligation for retrofitting measures. Guided by the costs of structural measures, the specific individual case is checked whether, in regards to the expected risk reduction, the costs are *proportionate* or *reasonable*. At the same time the Pre-Standard SIA 2018 (2004) contains the necessary regulations of risk-based evaluations of earthquake safety.

In the first step of the examination, the inspection and data acquisition, the compliance factor α_{eff} is the most important result. It is written as a number which measures up to which level the requirements for seismic design of new constructions in the current SIA structural standards are met. For this, the resistance at design level R_d, or the deformation capacity at design level, is proportioned to the seismic action effects at design level E_d.

$\alpha_{eff} = R_d / E_d$

When the compliance factor α_{eff} of the existing building reaches a value larger than or equal to one ($\alpha_{eff} \geq 1{,}0$ or 100 %), the design requirements for new construction are completely fulfilled. There is no further problem with this case, and the existing state of the building can be considered to be sufficiently safe for seismic behaviour.

However, the compliance factor α_{eff} for most existing buildings is less than one, that is to say that the design requirements of new construction are fulfilled only partially. The necessity of retrofitting measures is clarified on the basis of risk-based decision criteria, which are explained in Chapter 1.4. The lowest value of the compliance factor α_{eff} of all examined structural members of the building is the decisive value for earthquake safety.

1.4 Decisive factors for seismic retrofit

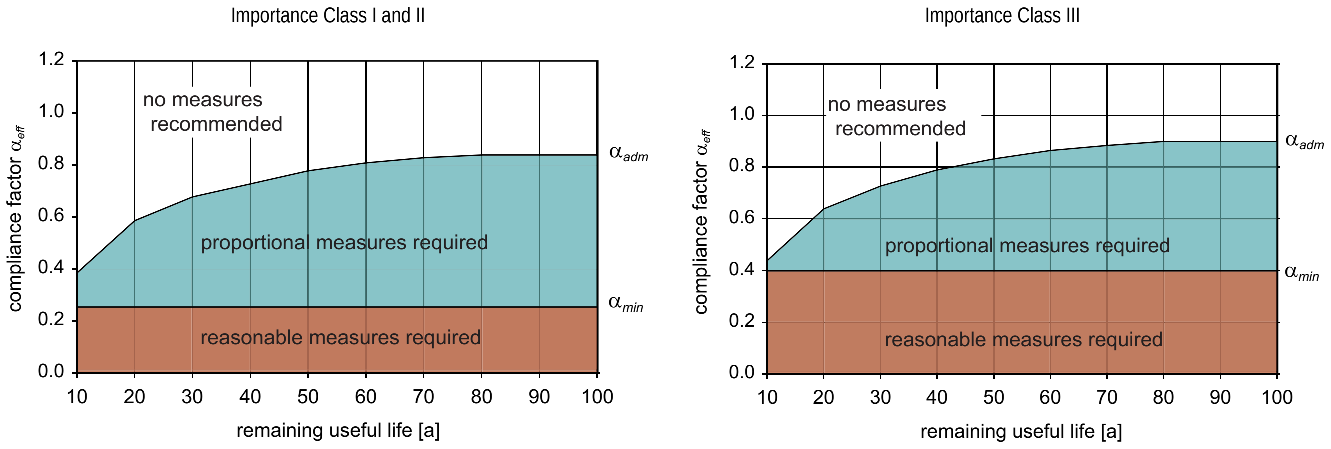
For existing buildings, in principle, the code requirement for new buildings should be reached, which means that the compliance factor α_{eff} should achieve a value greater than one. If the necessary retrofitting measures to achieve these requirements produce disproportionate costs, Pre-Standard SIA 2018 (2004) limits the measures to be realised such that costs remain *proportionate* or *reasonable*.

In the context of the examination of existing buildings, a *remaining useful life* as a period of time, based on guaranteed structural safety and serviceability is determined for operational and economical considerations. For typical types of buildings, it falls in the range of 20 to 50 years. At the end of the remaining useful life period, a further examination would be due.

The following three examples distinguish the necessity for measures of seismic retrofitting depending on the size of the compliance factor α_{eff}, the importance class, and the assumed remaining useful life of the building (Fig. 5):

Fig. 5 > Recommendations of measures according to Pre-Standard SIA 2018

Necessity for measures of seismic retrofitting for importance classes I and II (left) and importance class III (right) as a function of compliance factor α_{eff} and the remaining useful life of the building according to SIA 2018.



1. If the compliance factor α_{eff} of IC I or IC II falls under the lower threshold value of $\alpha_{min} = 0{,}25$, the individual risk is viewed as no longer acceptable, and seismic retrofitting measures are necessary as long as the costs remain *reasonable*.
   Life saving costs, to be at most CHF 100 million per human life saved, would be viewed as *reasonable*. If it is not possible to have acceptable individual risk without reasonable costs, then the risk will be limited by operational measures.
   The compliance factor α_{eff} of IC III is set to the higher threshold value of $\alpha_{min} = 0{,}40$. This guarantees minimal functionality of the building in the context of coping with a catastrophe.
2. If the compliance factor α_{eff} lies between the threshold values of α_{min} and α_{adm}, then the risk to people through seismic retrofitting measures is reduced so that the costs remain *proportional*.
   Life saving costs to a maximum of CHF 10 million per human life saved would be viewed as *proportional*.
3. If the compliance factor α_{eff} exceeds the upper threshold value of α_{adm}, then the existing state is acceptable.

The proportionality and the reasonableness of measures for seismic retrofitting are judged according to Pre-Standard SIA 2018 (2004) through a balancing of costs and benefits under consideration of safety demands of the individuals. Concerning costs, the costs for constructional measures to increase the earthquake safety under the term of *life saving costs* are understood. Concerning benefits, this is viewed as the reduction to individual risk in the form of avoided casualties or deaths. *Proportionality* applies to remedial measures with life saving costs up to CHF 10 million per human life saved and *reasonableness* with life saving costs up to CHF 100 million.

The boundary between proportionality and reasonableness is based on individual risk, meaning the likelihood for a single person, who is staying day and night in the building, to be killed due to earthquake consequences. This individual risk is acceptable when the probability does not exceed 10^{-5} per year. This is the case with a compliance factor α_{eff} higher than 0,25.

The reduction of risk will be calculated from the increase in compliance factors as a result of the considered retrofitting measure and the occupancy of the building. The occupancy is set as the average number of people in a year that the building holds. Often several retrofitting variations stay within proportional or reasonable costs. And, the one variation achieving the highest compliance factor should be selected for execution.

A detailed explanation of the risk-based assessment of eathquake safety according to Pre-Standard SIA 2018 (2004) can be found in SIA D 0211 (2005) and in BWG 2005. The compliance with Pre-Standard SIA 2018 and the other seismic regulations in the SIA structural standards is regulated for the building and real estate organizations of the Federal Government in directives from the Federal Department of Finance (EFD 2008). Other construction specialists and property owners are recommended to follow these directives.

2 > Strategies for seismic retrofitting

The goal of seismic retrofitting is the improvement of seismic behavior of structures. This can be achieved by different stategies. The choice of the optimal retrofitting strategy relies on a good understanding of the dynamic behaviour of engineering structures and a coordination with the future use of the structure.

Retrofitting for the dynamic seismic action requires some peculiarities in contrast to the usual procedure followed in strengthening for static loads. A seismically suitable retrofit should be optimally coordinated for the combination of three distinctive features of a structure: *stiffness, ultimate resistance* and *deformation capacity*. Retrofitting strategies should be avoided that are focused too strongly on one single distinctive feature of the structure without considering the possibly negative consequences of the other features.

The primary goal of retrofitting should be the correction of the main weakness relating to seismic performance. Besides the connection between new and the existing structural members, the important aspects are the transfer of the effects of the seismic action from the ground through the foundation.

In addition, the retrofitting strategy must take into consideration the future use of the building. In certain cases, the use can be improved as well with the necessary new structural elements.

2.1 Recommended strategies

With the exception of Strategy 1 “improving regularity”, the following introduced retrofitting strategies limit themselves for the sake of simplicity to the modification of a single distinctive feature of the structure (ultimate resistance, ductility, stiffness, damping, and mass). In practice, however, the modification of just one distinctive feature of the structure is mostly not realised. That is why more strategies are often combined for the application.

The structural behaviour before and after the implementation of the retrofitting strategy will be illustrated with the help of capacity curves. A capacity curve provides the simplified trend of the horizontal equivalent lateral force as a function of the horizontal displacement of the building and makes possible the comparison between the deformation capacity of the building and the deformation demand from the effects of the seismic action. A detailed explanation of this can be found in Standard SIA D 0211 (2005).

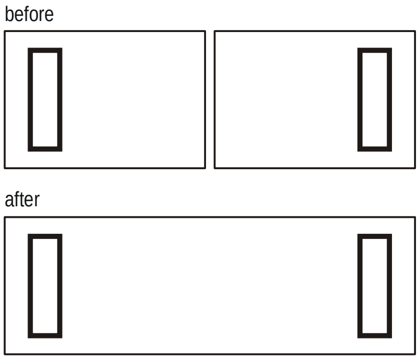
Strategy 1: Improving regularity

In principle, all structural retrofitting is aimed to achieve an improvement in regularity of the distribution of stiffness, resistance and mass of the structural system in elevation and in plan. The new structural members should fit in such a way that a regularity of the structural system is created.

A simple example for this strategy is the transformation from two originally separate halves of the building with an eccentric bracing system into a totally complete, symmetrically braced structural system (Fig. 6), such as what was done at the Neufeld High School in Bern (Example 12). A further application of this retrofitting strategy was done at the Auditorium HPH of ETH Zurich (Example 15), where through the introduction of a new steel truss system at the ground floor level, the regularity of the building in plan and in elevation was considerably improved.

Fig. 6 > Retrofitting strategy "improving regularity"

Through the closing of the existing expansion joint, two eccentrically braced building halves (before) are transformed into a symetrically braced building through two concrete cores located close to the end facades (after), as shown schematically in plan on the left.



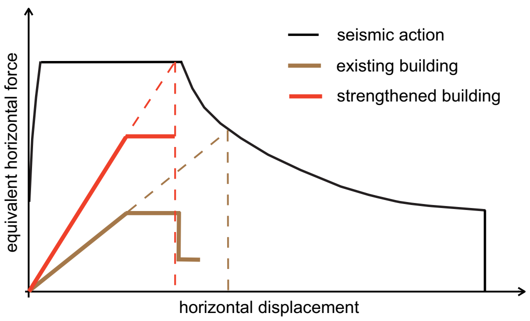
Strategy 2: Strengthening

The classical retrofitting strategy is the strengthening of existing structural systems through new building elements or through the doubling of existing building elements as, for example, through new reinforced concrete walls or steel trusses. With this strategy the resistance and the stiffness are increased, while the deformation capacity is practically unchanged. Thanks to the higher stiffness, the deformation demand from the seismic action can be reduced to the available deformation capacity.

The force displacement behaviour of the "strengthening" strategy is presented schematically in Figure 7 as so called capacity curves of the existing and the strengthened buildings. This strategy was most frequently used in the collection of examples presented in Chapter 3. An example of this is the substation in Basel with the strengthening through the yellow steel frame and the yellow reinforced concrete wall (Example 4) as shown in Figure 7.

Fig. 7 > Capacity curves of the retrofitting strategy "strengthening"

The capacity curves of the existing and the strengthened buildings are shown (equivalent horizontal force as a function of the horizontal displacement) in comparison with the demands of the seismic action.

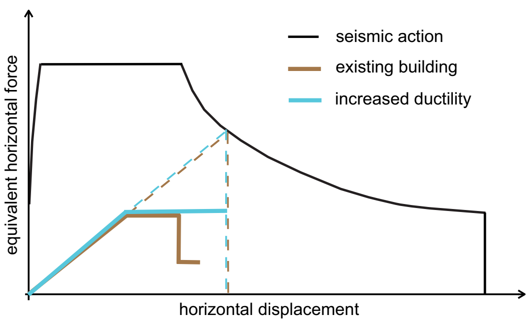


Strategy 3: Increasing ductility

The ductility is the plastic deformation capacity beyond the yield limit, or the limit of elastic deformation capacity. Brittle structural elements, for example masonry walls, could be made essentially more ductile by means of additional bonded strips. With this the entire deformation capacity (elastic and plastic) is increased, while the ultimate resistance and the stiffness are only slightly increased (Fig. 8).

Fig. 8 > Capacity curves of the retrofitting strategy "increasing ductility"

The increase in ductility produces a larger plastic deformation capacity, that means a longer horizontal leg of the capacity curve, to accomodate the displacement demand from the seismic action.



This strategy was not used alone in any of the examples of Chapter 3. As an example, the photograph in Figure 8 shows a masonry wall retrofitted with carbon fiber reinforced strips in a commerical building in Zurich.

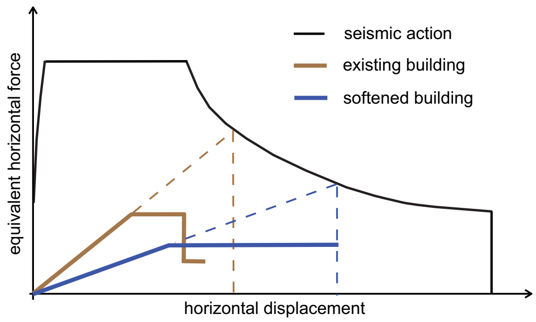
Strategy 4: Softening

A softening of the structural system through a reduction in the stiffness decreases the forces by simultaneously increasing the displacement from seismic action. A practical application of this strategy is the transformation of the longitudinal bearing system of a multi-span girder bridge from rigid to floating on a pier (Fig. 9).

Seismic isolation through the insertion of a horizontally soft, high damping seismic bearings made of reinforced rubber layers is a typical means of applying the strategy "softening". Thanks to the good damping quality of these specialty bearings a reduction of the seismic action occurs simultaneously as in strategy 5. A further possibility of softening exists in the removal of the stiff struts or infills so that the structural system can better deform horizontally.

Fig. 9 > Capacity curves of the retrofitting strategy "softening"

With softening, the stiffness is reduced as is the beginning of the slope of the capacity curve. It results in smaller forces, but larger displacements. The photograph on the right side shows an example of a floating longitudinal bearing system by means of lateral shear keys on a pier of a highway bridge in Basel, which originally contained a fixed longitudinal bearing system on one of the abutments.



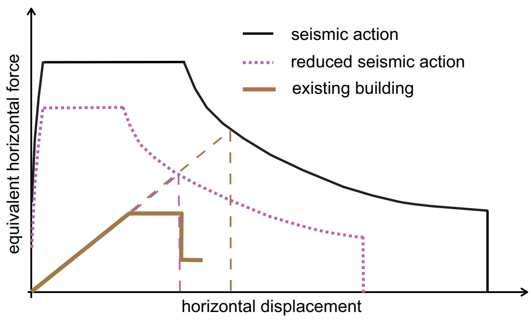
Examples of the retrofitting strategy "softening" are the fire station in Basel (Example 3), the Brunnen bridge on Simplon Highway A9 (Example 23) and the liquid gas tank in Visp (Example 24).

Strategy 5: Reducing seismic action through damping

An increase in damping causes a reduction in seismic action (Fig. 10). This can be realised through the insertion of additional dampers. Through seismic isolation by means of a horizontally soft, high damping seismic bearing, damping increases simultaneously with a reduction in stiffness (strategy 4), as was done in the three previously identified examples (the fire station in Basel, the Brunnen bridge and the liquid gas tank).

Fig. 10 > Capacity curves of the retrofitting stategy "reducing seismic action through damping"

With additional damping the seismic action can be reduced so much that the capacity curve of the existing building shows a sufficient deformation capacity. On the right, a high damping rubber bearing for seismic isolation of the fire station in Basel.



Strategy 6: Mass reduction

If the mass of a building is reduced, smaller inertial forces and also smaller stresses are produced from earthquakes. In practical terms, such mass reduction is done through clearing away of the roof level and some of the highest storeys. Mostly, however, the resulting reduction of useable space does not justify this strategy.

In principle, lighter elements should be given preference over heavier ones, as for example, by the replacement of non-structural members.

Strategy 7: Changing the use

A reduction of seismic action can be achieved not only through structural measures but also through operational ones, such as a permitted declassification of the building to a lower importance class. An emergency hospital of IC III could be converted into a convalescent house (IC II), for example, or a residential building (IC I). Seismic action will be reduced as a result of lower importance factors.

3 > Collection of examples from Switzerland

A collection of instructive examples of different types of structures located throughout Switzerland are presented. These projects were selected because they are representative examples for seismic retrofit. The majority are government buildings, reflecting current priorities of seismic prevention.

All the examples presented in this section are identified on the seismic zone map shown in Figure 11. The structures are arranged by their importance and seismic zone location, starting with buildings of the highest importance class III in the highest seismic zone Z3b to the buildings of lowest importance class I in the lowest seismic zone Z1. Lastly, two special structures, a highway bridge and a liquid gas storage tank, are presented as well as three buildings in which their existing state could be accepted without retrofitting.

Each example includes a description of the initial state before any seismic retrofit, a discussion as to its structural weakness regarding its performance during a seismic event, and the concepts of the seismic retrofit plan as well as a table summarising relevant data for each structure.

Further descriptions of technical terms listed in the summary table of relevant data can be found in the following chapters:

> ground type, see Appendix A1

> importance class, see Chapter 1.2

> seismic zone, see Appendix A1

> compliance factor (initial state) α_{eff}, see Chapter 1.2

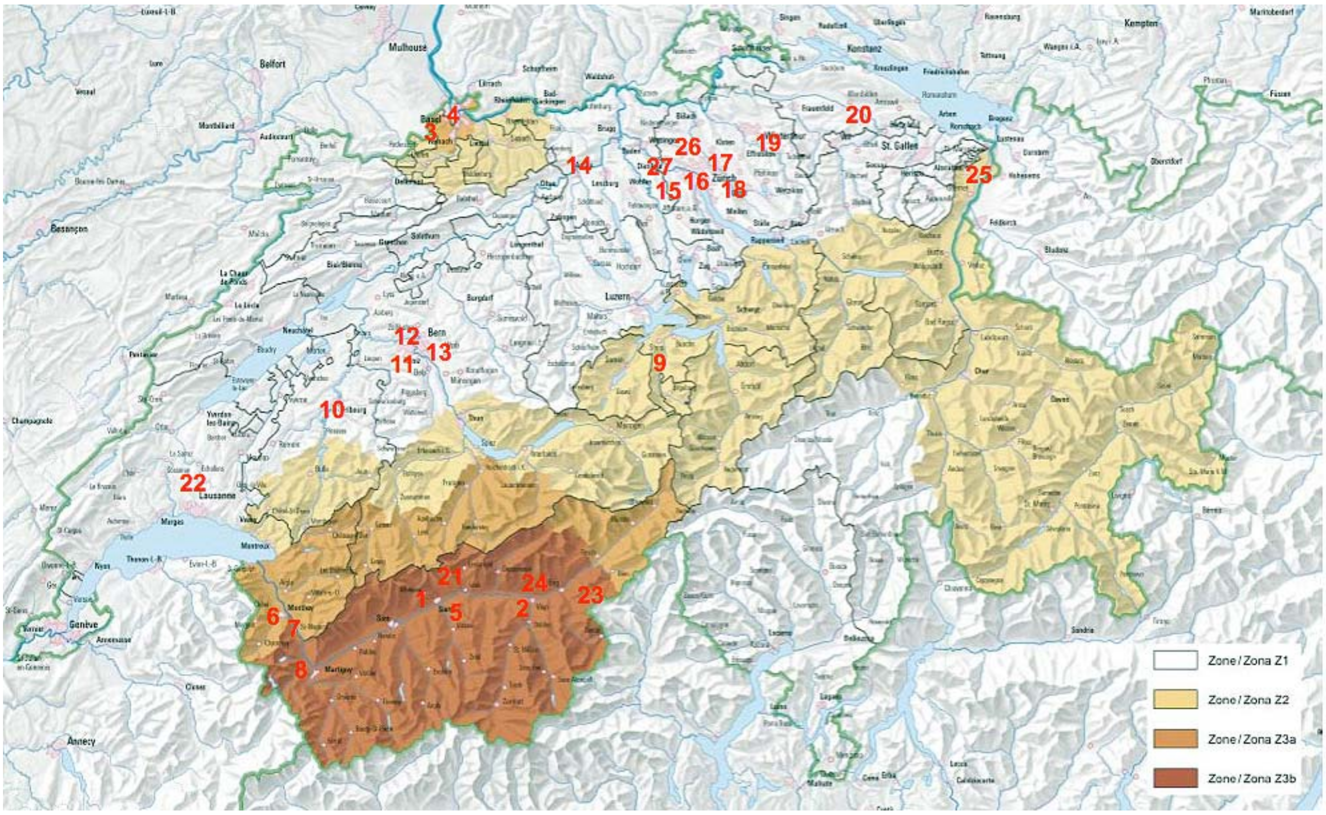
> compliance factor (retrofitted) α_{int}, see Chapter 1.2

> occupancy, see Chapter 1.4

> building value: insured value of the structure after retrofitting

Fig. 11 > Locations of the examples

Site locations of the examples on the seismic zone map of Swiss Standard SIA 261
Projects with retrofitting: Examples 1 through 24; Assessment without retrofitting: Examples 25 through 27



1	Cantonal police building in Sion VS	2	Fire station in Visp VS
3	Fire station in Basel	4	Substation in Basel
5	Residential and commercial building in Sion VS	6	School CO in Monthey VS
7	School ECS in Monthey VS	8	Municipal building in St-Maurice VS
9	Multi-purpose hall in Oberdorf NW	10	Residential building with shopping center in Fribourg
11	Government building in Bern	12	Neufeld High School in Bern
13	School in Ostermundigen BE	14	Children's hospital in Aarau
15	Auditorium HPH of ETH Zurich	16	School in Zurich
17	Radio station in Zürich	18	EMPA administration building in Dübendorf ZH
19	Residential building with shopping center in Winterthur	20	Friedberg High School in Gossau SG
21	Condominium in Crans-Montana VS	22	Hotel in Bussigny VD
23	Bridge on Simplon Highway A9 VS	24	Liquid gas tank in Visp VS
25	Residential building in Kriessem SG	26	Laboratory building HPP of ETH Zurich
27	SIA Office Tower in Zurich		

3.1 Cantonal police building in Sion VS

Initial state

The cantonal police station in Sion is a ten-storey, reinforced concrete building constructed in 1962. The command centre for the Canton's emergency service is located on the third floor. The basement houses the civil protection services.

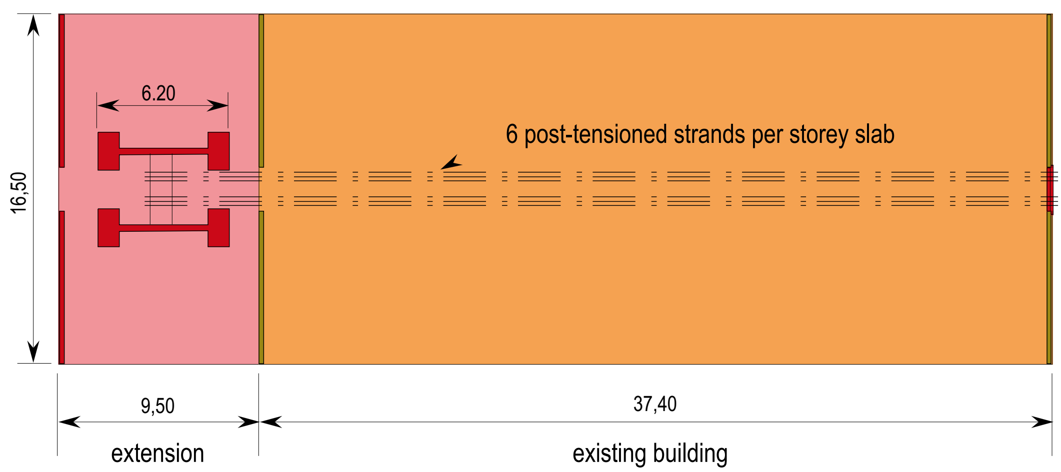
Structural weakness

This building was constructed at a time when seismic action was not a consideration. In the longitudinal direction, the building is insufficiently braced by two eccentric, reinforced concrete elevator and staircase cores. In the transverse direction, exterior reinforced concrete walls are available. The nonstructural elements, particularly the masonry walls and the suspended ceilings, do not fulfil seismic requirements needed in an emergency command centre of building importance class III (Koller 2000).

Retrofit plan

The existing building will be improved by the construction of an extension, which will provide horizontal support for seismic action. The choice of I-shaped reinforced concrete walls within the new extension reduces the torsional eccentricity on the entire system. The transverse stiffness of the new walls can be kept small compared to its longitudinal stiffness. The new extension is connected to the old part of the building through the installation of post-tensioned strands at every slab level in the longitudinal direction. The unreinforced masonry walls in the emergency command centre are separated from the structural system by joints and coated with polyester fabric, which secures the walls and prevents them from toppling out of plane. As a result, the masonry walls can follow the deformations of the building induced by an earthquake without getting damaged. Suspended ceilings and other installations are horizontally secured as well.

View of the longitudinal facade. The four, leftmost windows at each level are part of the extension.



Floor plan of the existing building (right) and the extension added afterwards (left) through which two I-shaped reinforced concrete walls provide bracing.

Highlights

The chosen retrofit concept permited a nearly unrestricted use of the building during the construction period. Realising the retrofitting measures in the new extension permitted the costs to be reduced compared to retrofitting the building without an extension.

Context

The Canton's risk study of essential facilities required the seismic assessment of the building.

View of the 6 anchorages of the tension strands in the cross girders between both new I-shaped reinforced concrete walls in the extension.

Transverse facade of the existing building showing the anchorages of the tension strands visible on the outside at each storey level.

Relevant data

Year of construction	1962
Building use	Emergency command centre
Occupancy	PB = 40
Building value	CHF 11 million
Importance class	IC III
Seismic zone	Zone Z3b
Ground type	Site specific, soil dynamic study
Compliance factor (initial state)	α_{eff} = 0,2 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting stategy	Strengthening, Increasing ductility
Year of retrofit	1998
Cost of retrofit	CHF 3 million or 29% of building value
Engineers	Résonance SA, CERT SA, P. Tissières
Architects	A. Bornet Fournier, P. Cagna

3.2 Fire station in Visp VS

Initial state

The fire station in Visp was constructed in 1974. The lower level serves a civil protection unit. The structural system of the main building is a reinforced concrete frame with masonry infills. An extension with reinforced concrete structural walls is located on the north side.

Structural weakness

The slender gable wall of unreinforced masonry on the south end of the building is the structural weakness for seismic behaviour. The in and out of plane stresses are of concern. In the longitudinal direction, the building is braced by the extension on the north side.

Retrofit plan

The critical gable wall at the south end will be strengthened by post-tensioning 8 CFRP-strips bonded to the inside of the wall. The CFRP-strips are anchored at the roof and the reinforced concrete slab of the first floor. Due to the post-tensioning, the gable wall can carry the earthquake action by small

The longitudinal facade of the rear of the fire station stiffened by the reinforced concrete structural wall at the left end.

The masonry gable wall strengthened by vertical CFRP-strips.

horizontal deformations respecting the damage limitation criteria for a building of importance class IC III. In addition, the post-tensioned CFRP-strips prevent the out of plane toppling of the wall.

Highlights

The installation of post-tensioned CFRP-strips has permitted continued operations without restriction.

Context

The seismic retrofit was done in the framework of general building preservation.

CFRP-strips post-tensioned from the roof (Truffer et al. 2004).

Two post-tensioned CFRP-strips on the inside of the gable wall (Truffer et al. 2004).

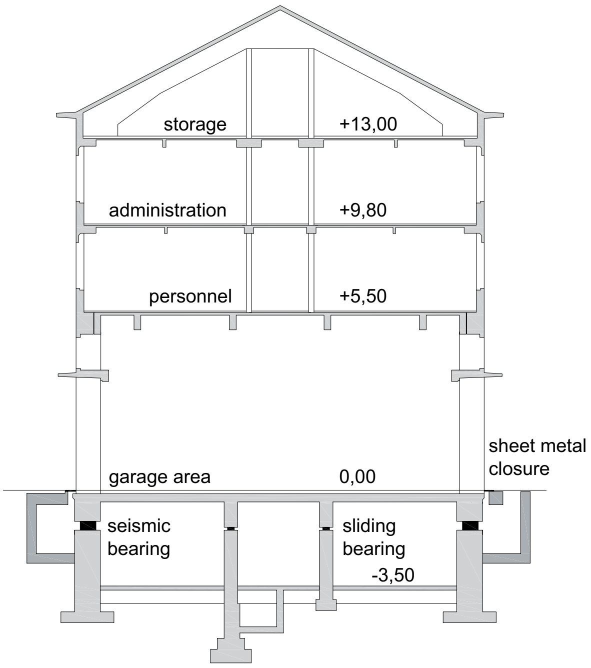
Relevant data

Year of construction	1974
Building use	Fire station
Occupancy	PB = 2
Building value	CHF 2 million
Importance class	IC III
Seismic zone	Zone Z3b
Ground type	Medium stiff (SIA 160)
Compliance factor (initial state)	α_{eff} = 0,4 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting strategy	Strengthening
Year of retrofit	2002
Cost of retrofit	CHF 35000 or 1,8% of building value
Engineers	BIAG Beratende Ingenieure AG, Visp Stresshead AG, Lucerne

3.3 Fire station in Basel

Initial state

The main building of Basel's Fire Station, the Lützelhof, was constructed out of reinforced concrete during World War II. The ground floor is an open floor plan over the entire area of 44 m by 15 m with 11 garage doors on both front and back faces of the building. There are three storeys above the ground floor for lounge areas and dormitories as well as room for the fire department's administration and storage.



Cross section through the building with the new seismic bearings in the basement (Bachmann, Zachmann 2008).

An expansion joint was installed around the building to permit the free, horizontal movement on the new seismic isolation bearings.

Structural weakness

The relatively thin columns on the ground floor between the garage doors create a typical soft storey. A relatively weak earthquake would cause failure of the columns. In addition, the walls and floors of the higher storeys are inadequate to carry the seismic forces (Bachmann 2007a).

Retrofit plan

The structure was retrofitted by seismic isolation. The upper storeys are separated from the basement by a horizontal cut beneath the ground floor slab and placed on seismic bearings. To allow the building to freely move horizontally during an earthquake, an allowance or gap is created on all sides. To this purpose, the length of the neighbouring buildings on both ends were reduced by 15 to 18 cm.

Highlights

The choice of using seismic isolation did not restrict the use of the garage during the installation, and business interruption was limited. Conventional strengthening of the ground floor by using reinforced concrete walls would have eliminated the use of two doors and the higher storeys would have required extensive work.

Installation of a seismic elastomeric bearing under a column in the outside wall of the basement.

Sliding bearings were installed under the column-free inner region of the ground floor.

Context

A risk analysis of the Canton's essential facilities required the seismic retrofit of the building.

Relevant data

Year of construction	1942
Building use	Fire station
Occupancy	PB = 60
Building value	CHF 13 million
Importance class	IC III
Seismic zone	Zone Z3a
Ground type	Site specific, soil dynamic study
Compliance factor (initial state)	α_{eff} = 0,2
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Softening, Reducing seismic action through damping
Year of retrofit	2007
Cost of retrofit	CHF 3 million or 23% of building value
Engineer	ZPF Ingenieure AG
Expert	Prof. Dr. Dr. h.c. Hugo Bachmann

3.4 Substation in Basel

Initial state

The substation Wasgenring of Industrial Works Basel (IWB) consists of an assembly shop above ground and extensive, three to four storey underground areas for electrical equipment. The building is classified as an essential building (IC III) because of its high importance for supplying electricity in the case of an emergency.

Structural weakness

While the massive basement made of reinforced concrete walls and floors is sufficiently earthquake resistant, the assembly shop in its original state does not meet the requirements. The structural system of the assembly hall is a minimumly reinforced concrete frame with masonry block infills, which would become overstressed from earthquake forces induced by the massive roof especially at the level of the row of windows.

Outside view of the assembly shop.

Retrofit plan

To carry the earthquake forces from the massive roof, all four facade walls must be strengthened. On the west side, a steel frame was installed and on the other remaining three sides, reinforced concrete walls were constructed. The walls were anchored by post-tensioned CFRP-strips in the reinforced concrete walls of the basement. The standard for the design is the 5% maximum storey drift criteria for masonry walls.

New A-shaped steel frame on the west facade and new reinforced concrete structural wall on the north facade of the assembly shop.

New reinforced concrete structural wall from the inside of the east facade of the assembly shop.

Highlights

Under the west facade, the entire width in the basement needs to be kept clear for the installation and removal of the larger transformers. The strengthening of the west facade was done by means of an A-shaped steel frame, whereby the vertical reaction force in the ground floor level is carried by steel plates in the basement while the transverse force can be taken by the slab.

Context

The seismic retrofitting was done on the occasion of the rehabilitation of the substation plant. It is part of the seismic retrofitting program of the IWB to secure its supply of electricity after an earthquake. (Koller 2008).

Threading of the CFRP-strips to the anchorage of the new reinforced concrete structural wall.

New A-shaped steel frame in the ground floor level of the west facade and new steel plates in the basement.

Relevant data

Year of construction	1964
Building use	Substation
Occupancy	PB = 0
Building value	CHF 12 million
Importance class	IC III
Seismic zone	Zone Z3a
Ground type	C
Compliance factor (initial state)	α_{eff} = 0,3
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	2006
Cost of retrofit	CHF 650 000 or 5 % of building value
Engineers	Résonance SA, Colenco AG, Stresshead AG

3.5 Residential and commercial building in Sion VS

Initial state

The four-storey residential and commercial building in Sion was constructed in 1965 as a composite steel and concrete structure. A retail business is located on the ground floor, and a medical office is located on the second floor. The higher storeys are an L-shaped floor plan. The structural system uses steel columns with composite decks and isolated reinforced concrete structural walls. Both lower levels are made of reinforced concrete.

Structural weakness

The structural system is highly irregular in both the floor plan as well as in elevation. Because of the large area of retail space needed at the ground floor, most of the bracing elements are missing. Under seismic actions the ground floor level forms a classic soft storey with torsion.

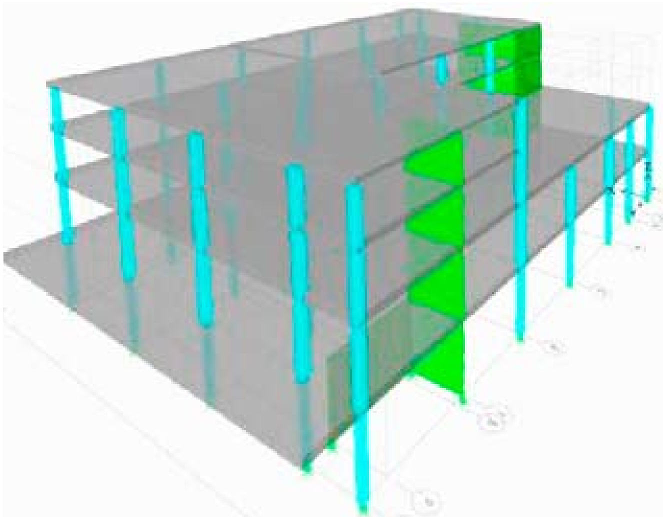
Retrofit plan

The building was strengthened by a new reinforced concrete core and a reinforced concrete wall both running through all of the upper storeys. The ground floor was further stiffened through a massive reinforced concrete frame. The new structural elements were anchored in the basement.

Highlights

New reinforced concrete frames were constructed in the ground floor level to provide as much space as possible for the shopping center. Self-compacting concrete was utilised for

New reinforced concrete frame in the ground floor level.



Finite element model of the building with the new reinforced concrete walls shown in green (Garcia-Vogel 2005).

the new structural elements. This made it easier to pour the concrete to meet the intersection with the existing floors.

Context

The seismic retrofitting was done together with a general redevelopment of the building by providing a new use for the upper level as medical offices.

Detail of the connection of the new wall's reinforcing bars with the existing floor (Garcia-Vogel 2005).

Installation of the reinforcing bars of the new reinforced concrete walls in the ground floor level.

Relevant data

Year of construction	1965
Building use	Shopping center, medical offices
Occupancy	PB = 85
Building value	CHF 4,5 million
Importance class	IC II
Seismic zone	Zone Z3b
Ground type	C
Compliance factor (initial state)	α_{eff} = 0,2
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening, Improving regularity
Year of retrofit	2005
Cost of retrofit	CHF 0,13 million or 3% of building value
Engineers	SD Ingénierie Dénériaz et Pralong Sion SA
Architect	Grégoire Comina, Sion

3.6 School CO in Monthey VS

Initial state

The school building of the «Cycle of Orientation» (CO) in Monthey was constructed in 1971 out of steel. The structural system is a steel frame in each direction. The floor deck consists of prefabricated, reinforced concrete slabs supported on secondary steel girders. The building is 39 m long and 34 m wide and rises four storeys high. The basement is constructed of reinforced concrete.

Structural weakness

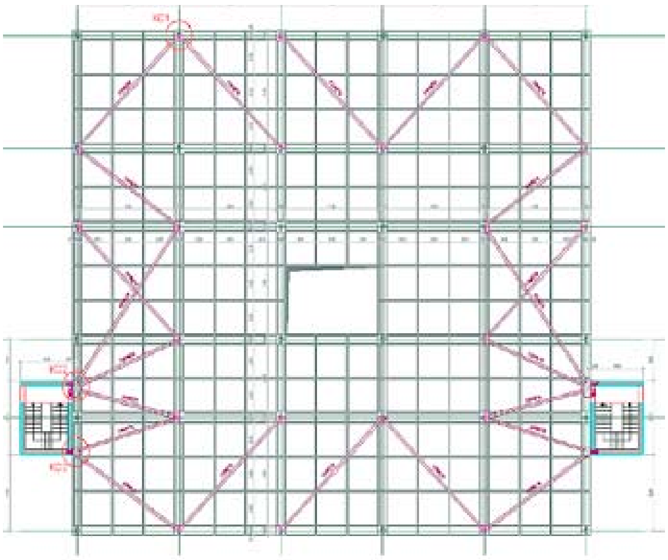
The steel construction of the CROCS system (Center of Rationalization and the Organization of Construction Scholars) was developed in western Switzerland in the 1960's. The connections of the steel frame are bolted with only two bolts connecting the beam web to the column. The connections can carry only a small fraction of the seismic forces. The diaphragm action of the prefabricated deck slabs are insufficient.

Retrofit plan

A new horizontal bracing system was constructed on the exterior of the building by adding two, reinforced concrete stairway towers extending through all of the floors. The floor slabs were strengthened by a new steel truss, which also provides for the transfer of horizontal forces to the stairway towers.

View of the new stairway tower on the south side of the building.

View of the new stairway tower on the north side of the building.



Floor plan of the building showing the new concrete stairway towers (green) and the new horizontal steel truss in the floor slabs (red).

Highlights

To fulfil the new fire protection regulations, it was going to be necessary for the building to have two new staircases anyway. With the integration of fire and seismic retrofitting in both reinforced concrete stairway towers, synergies were achieved.

Context

The seismic retrofitting was done together with a general redevelopment of the building and an increase in an additional storey.

Steel reinforcement in the basement and foundation of the new stairway towers.

Stairway tower and addition under construction (south side).

Relevant data

Year of construction	1971
Building use	School
Occupancy	PB = 76
Building value	CHF 24 million
Importance class	IC II
Seismic zone	Zone Z3a
Ground type	Microzonation Monthey «Zone Talrand»
Compliance factor (initial state)	$\alpha_{eff} = 0{,}16$
Compliance factor (retrofitted)	$\alpha_{int} = 1{,}0$
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	2007
Cost of retrofit	CHF 1,85 million or 7,7% of building value
Engineers	A. Schmid + R. Peruzzi, Kurmann & Cretton SA
Architect	PAI Planification, Lausanne

3.7 School ESC in Monthey VS

Initial state

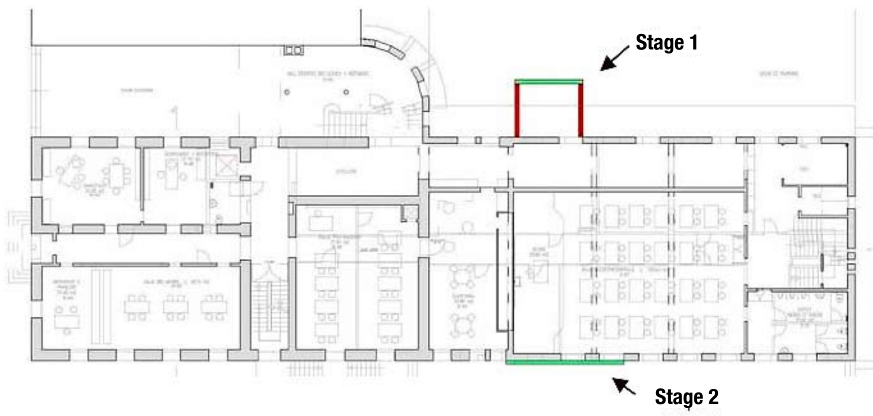
The older portion of the school building, today called the «Superior School of Commerce» (ESC), was constructed in Monthey in 1908. An addition in the longitudinal direction of the building was done in 1950, more than doubling its volume. The building has four storeys of solid, unreinforced masonry construction with a basement level. The floors in the older portion of the building are timber, and in the newer portion they are reinforced concrete.

Structural weakness

The relatively thin, single wythe walls in the addition create the weak situation with regards to seismic performance. The bracing in the transverse direction of the building is particularly insufficient. Partition walls are completely absent. This is the complete opposite in the old portion, which has several thick masonry walls. The anchorage between the facade walls

View of the rear facade with the new reinforced concrete elevator shaft.

Sketch of the rear facade with the new reinforced concrete elevator shaft in the middle of the building's newer portion. (Stage 1).



Floor plan of the older portion of the building (left) and the newer portion (right) with the new reinforced concrete elevator shaft (Stage 1) and the new reinforced concrete walls (Stage 2) (Peruzzi, Schmid 2007).

and the wooden floors is the structural weakness in the old portion of the building.

Retrofit plan

The newer portion of the building was strengthened by new reinforced concrete walls on both longitundinal sides. The new walls run throughout all the storeys of the building. In the first stage of the work, an elevator shaft was constructed on the rear side of the building, primarily to ensure bracing in the transverse direction. To resist the overturning moments, the foundation of the elevator shafts was secured to the foundation soil with twelve micropiles. In the second stage of the work, the front facade was supplemented by a rectangular reinforced concrete wall acting together with the elevator shaft to brace the building in the longitudinal direction. In the older portion of the building, anchorages between the facades and the wooden floors were installed.

Anchorage of the elevator shaft with Swiss-Gewi rods and grouted reinforcement in the existing reinforced concrete floors.

Construction of the foundation of the new reinforced concrete elevator shafts with micropiles.

Highlights

The construction work needed to be restricted to the exterior walls so that the ongoing school activities could be maintained. It was possible to make a janitor‘s room next to the elevator inside the new reinforced concrete shaft.

Context

The seismic retrofitting was done on the occasion of a renovation for a new use of the Canton‘s school building.

Relevant data

Year of construction	1903, 1908 and 1950
Building use	School
Occupancy	PB = 32
Building value	CHF 4,9 million
Importance class	IC II
Seismic zone	Zone Z3a
Ground type	Microzonation Monthey «Zone Talrand»
Compliance factor (initial state)	α_{eff} = 0,15
Compliance factor (retrofitted)	α_{int} = 1,0 (new portion) and α_{int} = 0,8 (old portion)
Retrofitting strategy	Strengthening
Year of retrofit	2004 through 2007
Cost of retrofit	CHF 0,54 million or 11 % of building value
Engineer	R. Peruzzi, Kurmann & Cretton SA
Architect	J.-M. Zimmermann

3.8 Municipal building in St-Maurice VS

Initial state

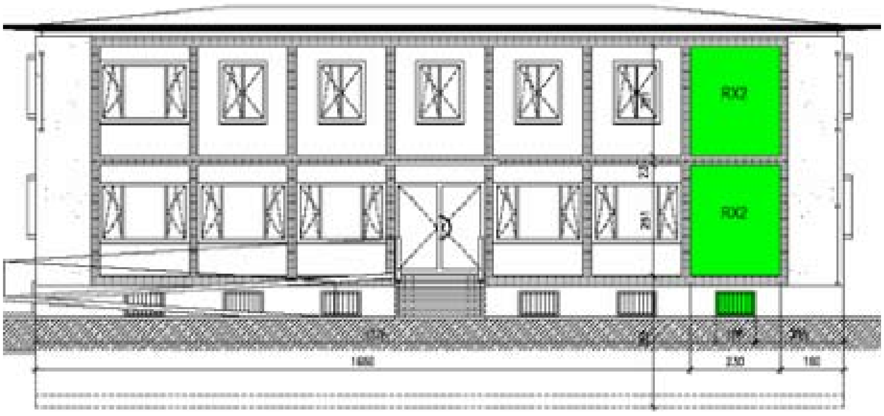
The two storey building in St. Maurice dates to the 1950's. In the transverse direction, the structural system consists of masonry walls and in the longitudinal direction out of reinforced concrete frames with partial masonry infills. The floors and the outer walls of the basement are out of reinforced concrete. The length of the building measures 20.5 m and the width is 10 m.

Structural weakness

The longitudinal facades are most problematic. At the ground floor the masonry wingwalls are shortened with half of the storey height unbraced and free to oscillate. There is danger of brittle shearing failure even from a weak earthquake.

View of the front longitudinal facade with the new reinforced concrete structural wall on the outside panel at the far right.

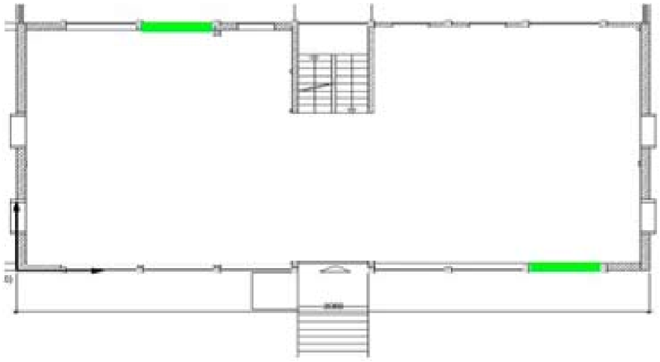
View of the rear longitudinal facade with the new reinforced concrete structural wall in the middle middle at the right.



Elevation showing the new reinforced concrete structural walls (green) in the front longitudinal facade.

Retrofit plan

A segment in each of the longitudinal facades was closed off with a slender reinforced concrete structural wall. Both new reinforced concrete structural walls were anchored in the exterior walls of the basement and extend up through both upper storeys. Now, in plan, there is a new symmetric bracing system in the longitudinal direction.



Floor plan showing both new reinforced concrete structural walls (green) in the longitudinal direction.

Highlights

Thanks to the large masonry walls of the facades, the building already achieves a compliance factor of 0,7 in the transverse direction. On the basis of the criteria of proportionality of Pre-Standard SIA 2018, retrofitting in the transverse direction not required because of the low occupancy (PB = 2,2) of the building.

Reinforcement of the new concrete structural wall in the front longitudinal facade.

Context

The seismic retrofitting was done in the context of a general redevelopment of the builidng for a new use as a training center.

Relevant data

Year of construction	1955
Building use	Training center
Occupancy	PB = 2,2
Building value	CHF 1,4 million
Importance class	IC II
Seismic zone	Zone Z3a
Ground type	C
Compliance factor (initial state)	α_{eff} = 0,17
Compliance factor (retrofitted)	α_{int} = 0,7
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	2005
Cost of retrofit	CHF 50000 or 3,5% of building value
Engineer	R. Peruzzi, Kurmann & Cretton SA
Architect	P.-P. Bourban

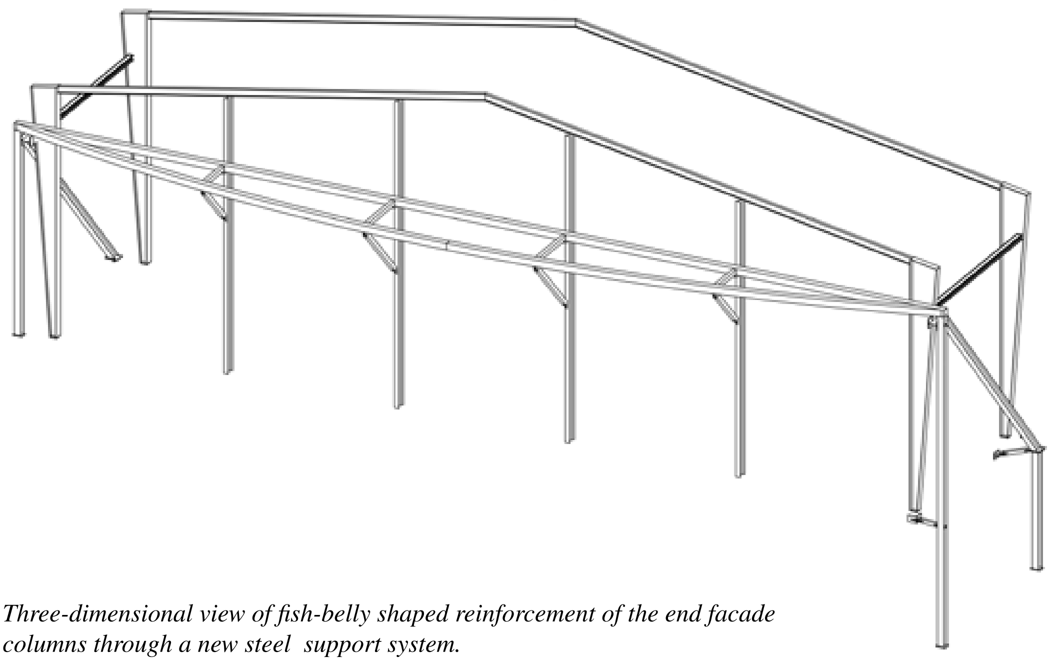
3.9 Multi-purpose hall in Oberdorf NW

Initial state

The multi-purpose hall of armasuisse Real Estate at the army camp in Oberdorf was constructed in the early 1970's using a standardised building system. The level occupied for the hall is 50 m long and 27 m wide. The basement is reinforced concrete and opens on one side. The structural system of the hall is composed of a two-hinged steel frame of IPE-Profile members running across the whole width. The frame is braced in the longitudinal direction through masonry infills.

Structural weakness

The main problem is due to wind and earthquake in the longitudinal direction of the hall. The horizontal truss in the roof of the hall shows constructional deficiencies in the connection design. In addition, the horizontal bracing of the two-hinged frame in the longitudinal direction of the hall is insufficient. In the transverse direction the ultimate resistance of a strong, 10 m high steel frame is sufficient for wind and earthquake. The steel frame remains in the elastic region under the seismic action of zone Z2.



Three-dimensional view of fish-belly shaped reinforcement of the end facade columns through a new steel support system.

Retrofit plan

The retrofit plan is primarily focused on wind action in the longitudinal direction. The facade columns and the outermost two-hinged frames in both end facades were supported by new horizontal, fish-belly shaped steel frames in the upper area. The resulting horizontal longitudinal force at the ends of the steel frame is directed through a strong diagonal in the basement.

Highlights

The retrofit plan will be modularly developed for approximately thirty multi-purpose halls of the same building type. The wind module consists of a steel structural system for strengthening both end facades. For the locations in higher seismic zones, as here in Oberdorf NW in zone Z2, the seismic module will be additionally mounted. Both endfacing steel support systems will be joined through longitudinal girders running on both sides of the roof edge. The additional cost of the seismic module amounts to about 15% of the cost of the wind models.

Context

The seismic retrofit was done in the context of a systematic examination program of standardised halls belonging to armasuisse Real Estate.

Edge column of the fish-belly shaped reinforcement of the lower storey.

Fish-belly shaped reinforcement in the end facade columns.

Relevant data

Year of construction	1973
Building use	Sport hall
Occupancy	PB = 5
Building value	CHF 5 million
Importance class	BWK II
Seismic zone	Zone Z2
Ground type	C
Compliance factor (initial state)	α_{eff} = 0,1
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening
Year of retrofit	2007
Cost of retrofit	CHF 25000 or 0,5% of building value
Engineers	Ernst Winkler + Partner AG, Emch + Berger AG

3.10 Residential building with shopping center in Fribourg

Initial state

The Beauregard-Center in Fribourg consists of three 8-storey residential buildings dating from 1970. A shopping center is located in the ground floor level. Two lower levels are used for parking and storage. The structural system exists in the higher storeys as unreinforced masonry walls, which in the ground level rests on reinforced concrete columns. The floors are reinforced concrete.

Structural weakness

In its original state, the building has a typical, horizontally weak ground level (soft storey). This is due to the transition from masonry walls in the residential regions of the upper storeys to reinforced concrete columns in the shopping center. The structural weakness referring to seismic performance are the columns in the ground floor and especially the insufficient reinforcement in the beam to column connections. In addition, a few masonry walls have insufficient structural capacity.

New external reinforced concrete structural wall will be concreted against the existing facade (Lateltin 2003).

View of the new external reinforced concrete structural wall.

Retrofit plan

The plan was for the building to receive a new structural system for horizontal actions in both principal directions in plan consisting of two, slender reinforced concrete walls extending through all storeys. The new walls are anchored on micropiles in the foundation soil.

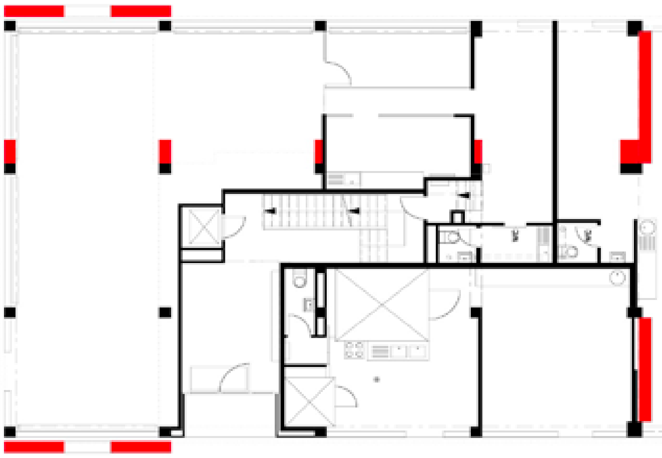
Highlights

The connection of the new structural walls to the end faces of the floors was done by using grouted dowels.

Context

The seismic retrofitting was done in the context of extensive structural preservation measures to extend the use of the building for another thirty years.

Reinforcement detail of the new conrete structural wall with grouted dowels in the existing floors.



Floor plan of the ground floor level with the new reinforced concrete walls (Lateltin 2003).

Relevant data

Year of construction	1970
Building use	Residential building over shopping center
Occupancy	PB = 135
Building value	CHF 23 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	Stiff
Compliance factor (initial state)	α_{eff} = 0,5 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting strategy	Strengthening, Improving regularity
Year of retrofit	2002
Cost of retrofit	CHF 1,7 million or 7,4% of building value
Engineer	Centec SA Ingénieurs Conseils
Architect	Lateltin & Monnerat architectes SIA SA
Expert	Prof. Dr. Peter Marti

3.11 Government building in Bern

Initial state

The Bernerhof, the current seat of the Federal Department of Finance, was constructed in 1855–57 following the building plans of Friedrich Studer. The characteristic structural members of this representative six-storey building are walls constructed of natural stone masonry walls and timber beam floors. The building stands under protection as an historical monument.

Structural weakness

The timber beam floors and the natural stone masonry walls form the structural weakness relating to seismic performance. The transfer of horizontal force from the timber beam floors in the walls is particularly insufficient. Some of the walls are interupted in the ground floor. In addition, for some walls the out-of-plane stability is critical.

View of the east facade.

Substitution of reinforced concrete floors for the existing timber beam floors in the east wing.

Retrofit plan

The retrofit plan must be coordinated with the historical monument protection aspects. In the east wing of the building, the existing timber beam floors were replaced by concrete floors. The remaining timber beam floors were strengthened in the critical regions by composite timber concrete floors. The new stairways were constructed out of reinforced concrete and extend through all storeys.

Highlights

With the exception of the end walls on the north side, the compliance factor could generally be increased to 1,0. Considering the requirements of historical monument protection, the end walls were left in their original state because a collapse would result only in locally, limited consequences.

Context

The seismic retrofit was done in the context of a complete renovation of the building.

Anchorage reinforcement of the new floor in the masonry walls.

Concrete floor in the region of a new access shaft.

Relevant data

Year of construction	1857
Building use	Public administration
Occupancy	PB = 105
Building value	CHF 45 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	E
Compliance factor (initial state)	α_{eff} = 0,1
Compliance factor (retrofitted)	α_{int} = 1,0 (north endwalls α_{int} = 0,1)
Retrofitting strategy	Strengthening
Year of retrofit	2004
Cost of retrofit	CHF 0,2 million or 0,4% of building value
Engineer	WAM Partner AG

3.12 Neufeld High School in Bern

Initial state

The Neufeld High School in Bern was built in 1965 as a reinforced concrete structure. It consists of a basement, a ground floor, and four upper storeys. The outside dimensions in plan are 69 m by 37 m. The structural system consists of reinforced concrete columns with two reinforced concrete elevator shafts. The floors are also made of reinforced concrete.

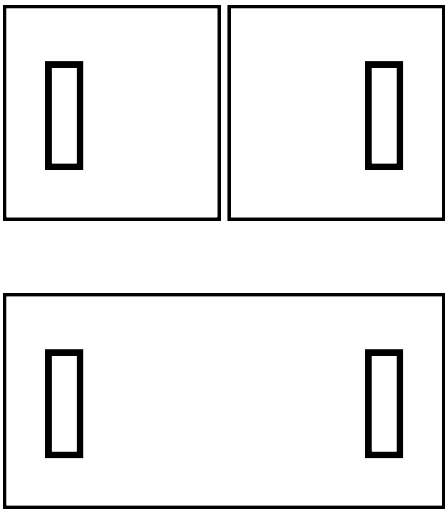
Structural weakness

In its original state, the building was subdivided through all storeys into two halves by an expansion joint. Each half was eccentrically braced by an elevator core. Because of the torsional bending vibrations of both parts, there is danger of the slab unseating at the expansion joint even from weak earthquake excitation. As seen from the outside, the building has an architecturally open, weak ground floor. However, as both solid elevator cores are running through all storeys, the building possesses a regular structural system in elevation.

Retrofit plan

The original expansion joints of the storey floors in the middle of the building were closed. As a result, a combined system symmetrically braced by the two existing slender reinforced concrete elevator cores was formed. A retrofit to an even higher level was associated with disproportionate costs.

View of the end facade of the building.



Floor plan of the initial state with two eccentrically braced building halves (above) and floor plan of the retofitted state with a centrically braced building (below).

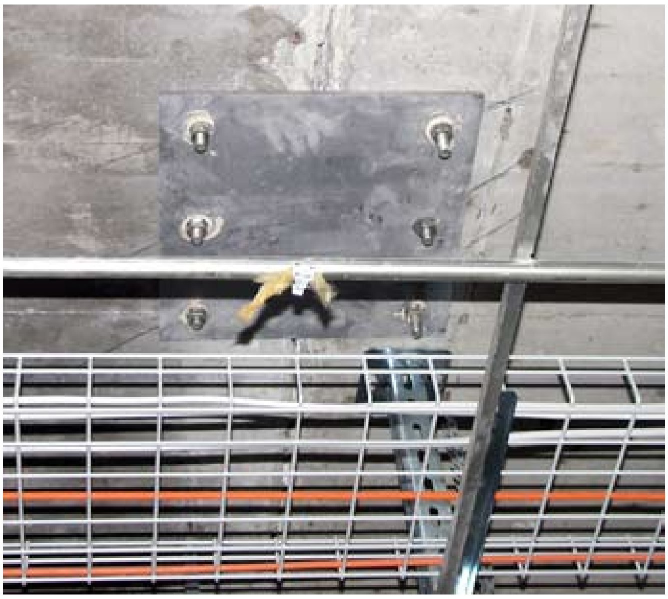
Highlights

The reconstruction of the elevators requires certain adaptations of the elevator shafts by locally strengthening them with bonded carbon fiber strips.

Context

The seismic retrofitting was done in the context of extensive structural preservation measures after 40 years of building use.

Strengthening of the elevator shafts with bonded carbon fiber strips.



Closure of the dilatation joint in the storey floors with steel plates arranged on both sides.

Relevant data

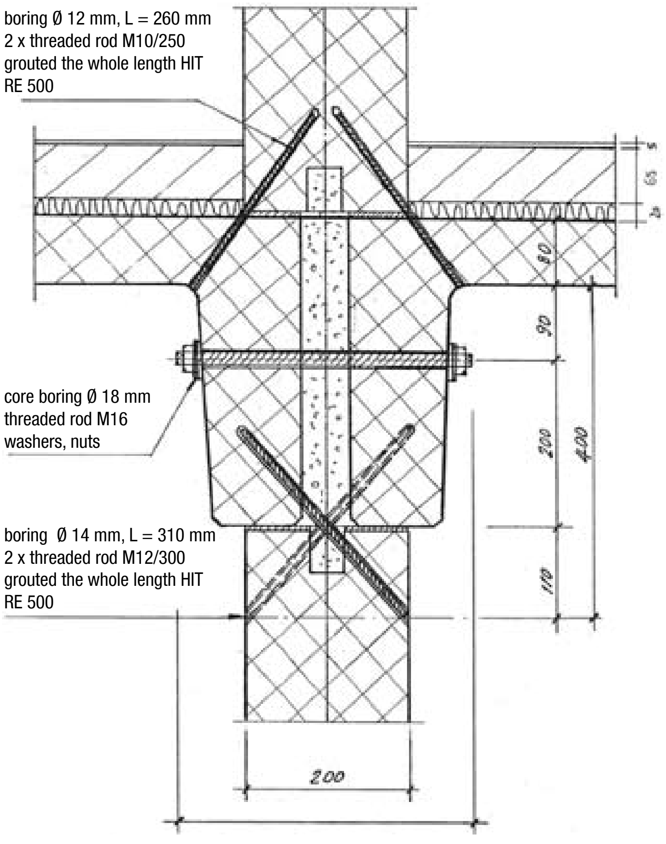
Year of construction	1965
Building use	School
Occupancy	PB = 200
Building value	CHF 43 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	E
Compliance factor (initial state)	α_{eff} = 0,1
Compliance factor (retrofitted)	α_{int} = 0,5
Retrofitting strategy	Improving regularity
Year of retrofit	2006
Cost of retrofit	CHF 0,3 million or 0,7 % of building value
Engineers	Marchand + Partner AG

3.13 School in Ostermundigen BE

Initial state

The school campus Rüti in Ostermundigen was constructed at the end of the 1960's using prefabricated methods of building construction. It comprises a five and a two-storey classroom building as well as a gymnasium. Columns, beams and walls are made of prefabricated concrete sections. The floor slabs are constructed as waffeled coffer elements.

The connecting walkway was retrofitted through the reinforced concrete walls in the longitudinal direction.



Cut through the modification of the coffer slab showing the new structural components.

Structural weakness

The individual prefabricated elements were put in place one after another without connections, such that no clear cut structural system for horizontal action can be identified. The diaphragm action of the coffered ceiling is insufficient. A total collapse is threatened from an earthquake, just like a house of cards.

Retrofit plan

The retrofit plan is to connect the prefabricated elements together by steel rods, straps, and plates. In addition, individual wall elements were strengthened with vertically running CFRP-strips and anchored to the basement in cast-in-place concrete.

Highlights

With regard to the criteria of proportionality, the seismic retrofit plan could be limited to the connection of the prefabricated members without adding a new horizontal bracing system. The following relevant data refers to the five-storey classroom building.

Additionally installed steel straps for the connection of the coffer slab with the walls.

Steel plates for the connections of the roof elements.

Context

The seismic retrofit plan was done in the context of a general renovation of the school campus.

Relevant data

Year of construction	1968
Building use	School
Occupancy	PB = 38
Building value	CHF 8 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	E
Compliance factor (initial state)	$\alpha_{eff} = 0{,}24$
Compliance factor (retrofitted)	$\alpha_{int} = 0{,}6$
Retrofitting strategy	Strengthening
Year of retrofit	2008
Cost of retrofit	CHF 140000 or 1,8% of building value
Engineer	Marchand + Partner AG

3.14 Children's hospital Aarau

Initial state

The children's clinic in the Canton Hospital in Aarau was built in 1954. The building is 55 m long, 16 m wide and has four upper storeys and two basement levels. The structural system consists of unreinforced masonry walls and concrete columns connected through relatively thin reinforced concrete floors.

Structural weakness

There is no verifiable bracing system in the longitudinal direction. The row of reinforced concrete columns next to the corridor and connected to a 1 metre deep beam form a longitudinal frame with shear critical, short columns (Koller 2000). In the transverse direction, the building is braced through the end facades of unreinforced masonry. Because the floors were designed as one-way slabs in the transverse direction, the gable walls receive little axial force and, therefore, can carry only insignificant horizontal forces from seismic action. A further weakness turned out to be the use of single and strip foundations instead of a rigid basement.

Retrofit plan

In the longitudinal direction, two new reinforced concrete walls running through all storeys were added, one of which will be constructed as a particularly ductile, coupled wall. For the bracing in the transverse direction, a 5.2 m long and 28 cm thick wall was concreted on both existing masonry gable walls. A third reinforced concrete wall was placed in the middle of the building in order to reduce the forces on the long floor slabs.

View of the longitudinal facade on the playground side.

Highlights

The design and detailing of the coupled, reinforced concrete structural walls followed the recommendations in (Paulay 1992). The steel reinforcement available in Switzerland at that time had an insufficient ductility for earthquake resistance even though it satisfied the requirements of Swiss Standard SIA 162. Special, highly ductile steel reinforcement was imported for the plastic regions (Koller 2000).

Context

The spark for an extensive structural perservation measure was the insufficient fire protection. In this context the earthquake safety was also examined. Of the total preservation costs, 6% were associated with seismic retrofitting.

Reinforcement of the new coupled reinforced concrete structural walls in the ground floor level with diagonal bundled bars in the coupling beams.

New coupled reinforced concrete structural walls in the basement.

Relevant data

Year of construction	1954
Building use	Clinic
Occupancy	PB = 350
Building value	CHF 24 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	Site specific, soil dynamic study
Compliance factor (initial state)	α_{eff} = 0,1 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	1999
Cost of retrofit	CHF 0,9 million or 4% of building value
Engineers	Peter Zumbach, Aarau, Résonance SA

3.15 Auditorium HPH of ETH Zurich

Initial state

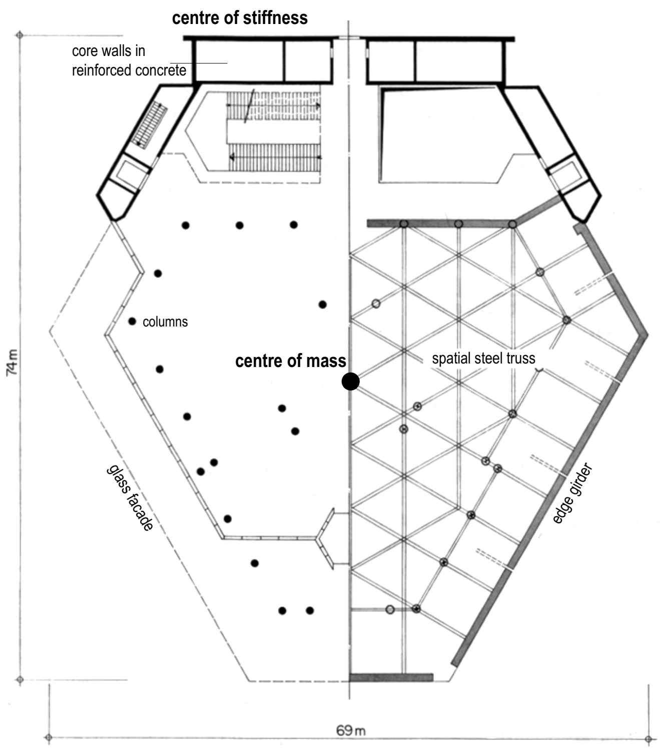
The large auditorium building HPH of ETH Zurich on the Hönggerberg was constructed in 1970–71 without regard to seismic action. It includes three auditoriums with a total seating for 1200 people over a large entrance hall with access to the cafeteria.

Structural weakness

The structural weakness referring to seismic performance of the original building is the open entrance hall under the supporting floor of the auditoriums creating a typical weak storey (soft-storey). In addition, there is a very large eccentricity of over 40 metres between the centre of stiffness of the reinforced concrete walls on the rear side of the ground floor level and the centre of mass of the overlying storeys. As a consequence, the building experiences severe torsional stresses under seismic action.

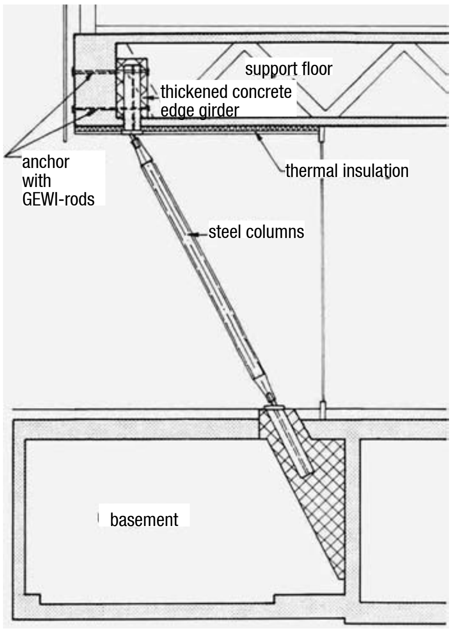
Retrofit plan

The weak ground floor level was retrofitted with a new, inclined, steel pipe truss. In this way, stiffness and resistance could be increased and the unfavorable eccentricity of the bracing system in the ground floor level could be eliminated.



Floor plan through the ground floor level (left) and through the hollow space of the support floor (right) with the locations of the centres of mass and stiffness in the initial state before the retrofitting (Schefer, Zwicky, Santschi 1995).

New inclined steel pipe truss in the ground floor level.



Cut through the new inclined steel pipe truss in the ground floor level (Schefer, Zwicky, Santschi 1995).

Highlights

The new steel pipe truss also provides gravity load supports to the cantilevered portion of the supporting floor, which were insufficient in the initial state. With limiting the structural improvement to a single storey and eliminating the need for a new foundation, the cost for the retrofit plan was limited to 0,7% of the value of the building.

Context

The seismic retrofit plan was done on the occasion of a renovation of the support floor over the ground floor level for gravity loads. This building was the first in Switzerland to be improved for earthquake safety by structural measures.

Relevant data

Year of construction	1970/71
Building use	Auditorium
Occupancy	PB = 200
Building value	CHF 70 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	Medium stiff
Compliance factor (initial state)	α_{eff} = 0,25 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting strategy	Improving regularity, Strengthening
Year of retrofit	1994
Cost of retrofit	CHF 0,5 million or 0,7 % of building value
Engineer	Basler & Hofmann, Ingenieure und Planer AG
Architect	Broggi & Santschi Architekten AG
Expert	Prof. Dr. Dr. h.c. Hugo Bachmann

3.16 School in Zurich

Initial state

The five-storey secondary school building of Riedenhalden in Zurich-Affoltern was built at the end of the 1950's. Four extensions with classrooms are arranged around a central square staircase. The floors and the walls in the staircase are made of reinforced concrete, the other walls are masonry.

Structural weakness

The existing reinforced concrete walls in the staircase have too little vertical and horizontal reinforcement. There is no bracing in the roof level over the staircase. The reinforced concrete roof level rests on pendular columns. The masonry walls in the extensions are interrupted through the rows of windows and can carry practically no horizontal loads.

Strengthening of an existing reinforced concrete wall with a 15 centimetre thick double wall.

Bracing the roof level with new steel frames.

Retrofit plan

The existing four walls of the staircase were strengthened by doubling the wall thickness. The four double walls are symmetrically arranged in plan and extend from the basement up to the roof level. The roof level was braced by four new steel frames, which were fitted around the windows and over the reinforced composite walls in plan.

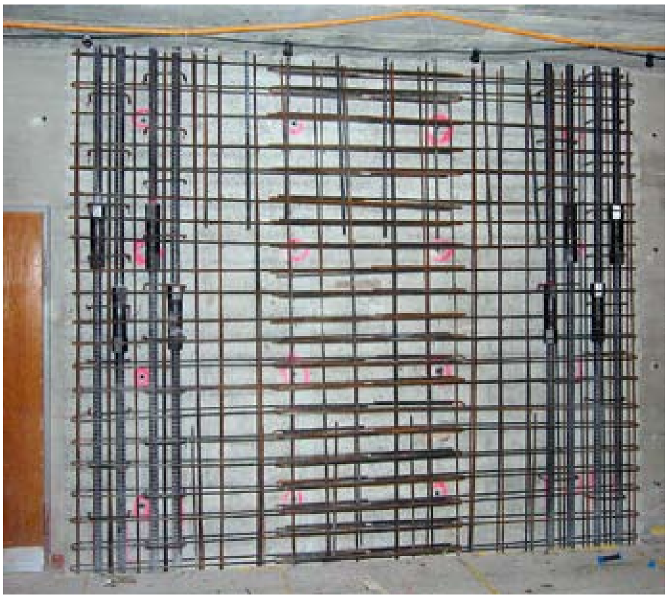
Highlights

Because the school building is protected as an historical monument, a retrofit plan was chosen in which the original appearance of the building would be adversely affected as little as possible.

Context

The seismic retrofit plan was done in the context of restoration and renewal of the nearly 50 year old school building.

Detail of the vertical reinforcement couplers in the double wall.



Reinforcement in the composite wall with vertical reinforcement couplers.

Relevant data

Year of construction	1958
Building use	School
Occupancy	PB = 48
Building value	CHF 4 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	E
Compliance factor (initial state)	$\alpha_{eff} = 0,2$
Compliance factor (retrofitted)	$\alpha_{int} = 1,1$
Retrofitting strategy	Strengthening, Improving regularity
Year of retrofit	2006
Cost of retrofit	CHF 0,13 million or 3% of building value
Engineer	Walt + Galmarini AG
Architect	Pfister Schiess Tropeano & Partner Architekten AG

3.17 Radio station in Zurich

Initial state

The high rise building of Swiss Radio DRS in Zurich was constructed in 1969 to 1970 without consideration of seismic action. The building has eight storeys of office and studio rooms. The building is a skeleton construction of cast-in-place concrete, which is stabilised through the reinforced concrete cores in the region of the elevators and stairs on both end faces of the building.

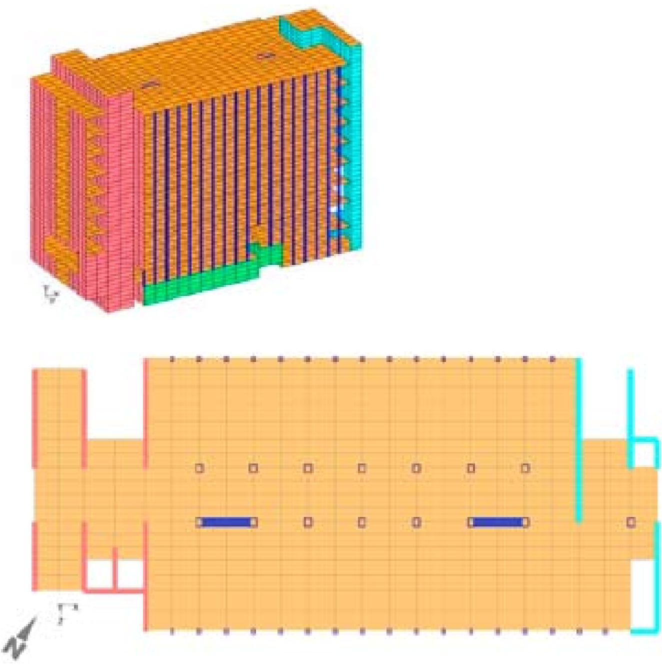
Structural weakness

In its original state, the building shows suffficient bracing in the transverse direction over the entire height through reinforced concrete structural walls. In contrast, in the longitudinal direction sufficient bracing is absent. There are only a few short longitudinal walls existing in the region of the cores.

Retrofit plan

Two new eccentric steel frames were constructed as the retrofit for the insufficient longitudinal bracing. The new steel frames are located between two existing reinforced concrete columns along the original corridor wall as can be seen in the floor plan (shown in dark blue in the sketch). The frames were anchored in the basement level on existing walls and foundations.

The steel framework was welded in two storey-height sections and delivered to the construction site. After the installation, the sections were bolted together. The connection to the existing concrete floor was done at each storey level through connecting reinforcement set in a prepared recessed area and then covered over with concrete.



Finite element model for the examination of the seismic safety of the building (above), floor plan with existing reinforced concrete support walls and new steel frames (dark blue, below).

New eccentric steel framework constructed between two existing reinforced concrete columns.

New eccentric steel framework with a column disguise.

Highlights

The new eccentric framework fits in well with the new architectural plan to create more transparancy by removing the existing corridor walls.

Context

The seismic retrofit plan was done together with other preservation measures in the 35 year old building.

Relevant data

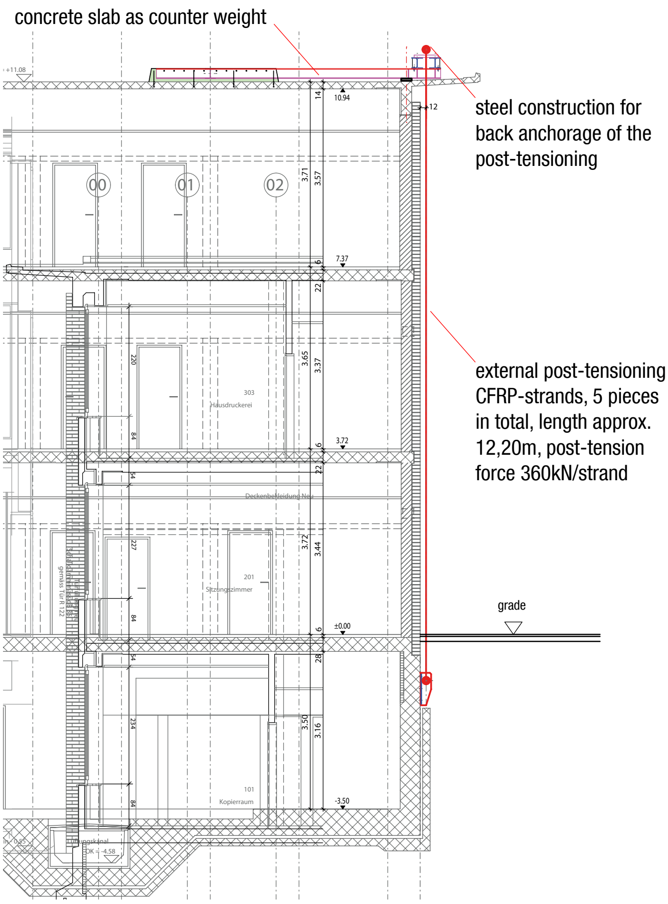
Year of construction	1970
Building use	Radio Staion
Occupancy	PB = 150
Building value	CHF 15 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	Medium stiffness
Compliance factor (initial state)	α_{eff} = 0,3
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	2004
Cost of retrofit	CHF 0,34 million or 2,3% of building value
Engineers	Federer & Partner, Bauingenieure AG Basler & Hofmann, Ingenieure und Planer AG
Architect	Di Gallo Architekten

3.18 EMPA administration building in Dübendorf ZH

Initial state

The three-storey administration building of the EMPA Dübendorf is approximately 50 m long and 18 m wide. It was constructed in 1960 in mixed construction of reinforced concrete frames, reinforced concrete walls and masonry. The floors are reinforced concrete.

Northern end facade strengthened by external vertical carbon fiber tension rods.



Longitudinal cut through the northern end facade with external carbon fiber tension rod.

Structural weakness

In the building's longitudinal direction, the existing reinforced concrete frame and the reinforced concrete walls of the staircase and elevator shafts are able to carry the seismic forces. In the building's transverse direction, the horizontal bracing system consists from both end facades of the masonry together with the core. In plan, the core is layed out eccentrically near the southern end facade. This facade is sufficient in its initial state, whereas the northern end facade, which is further away from the core, is overloaded from seismic forces.

Retrofit plan

The northern end facade, a 22 cm thick masonry wall, was strengthened by five 13 m long tension rods positioned on the outside. This was the first time that tension rods reinforced with carbon fiber were applied for seismic retrofitting (Bachmann 2007b). The eccentrically acting vertical post-tension force was transfered centrically to the end facade by means of a steel construction on the roof.

Upper anchorage of the carbon fiber tension rod on the roof from where the post-tensioning occurs.

Lower anchorage of the carbon fiber tension rod on the side of the basement wall.

Highlights

The vertical carbon fiber tension rods were fastened in front of the facade as a nice visible architectural element.

Context

The seismic retrofit was done together with the general renovation of the facade.

Relevant data

Year of construction	1960
Building use	Office building
Occupancy	PB = 80
Building value	CHF 9 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	E
Compliance factor (initial state)	α_{eff} = 0,25
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening
Year of retrofit	2007
Cost of retrofit	CHF 0,15 million or 1,5% of building value
Engineer	Synaxis AG Zurich
Architect	Raumfachwerk Architekten AG
Experte	Prof. Dr. Dr. h.c. Hugo Bachmann

3.19 Residential building with shopping center in Winterthur

Initial state

The four-storey building was constructed in the 1960's in mixed construction of masonry with reinforced concrete. Appartments are located in the upper storeys. The shopping centre in the ground floor spans nearly three surfaces of the upper storeys. The storey floors and the basement are reinforced concrete.

Structural weakness

The building exhibits a pronounced soft storey in the ground floor with large torsional effects under seismic action. In addition, there is an expansion joint in the middle of the building's length with adverse effects on the seismic behavior. During earlier reconstructions several walls in the ground floor were removed so that no actual bracing system exists anymore.

New V-shaped steel truss in an office room on the ground floor level.

New V-shaped steel truss hidden behind a shopping aisle shelf in the ground floor.

Retrofit plan

In the ground floor a total of four new V-shaped steel trusses were built, two per building direction. The vertical reactions of the trusss are carried by new steel columns through the basement and anchored with micropiles. The horizontal reactions of the trusses were picked up by the existing floor slabs of the ground floor level.

Highlights

The main advantage of steel assemblages against other retrofitting options is in the short construction time. The reconstruction of the retail shop needed to be completed within two months.

Anchorage of the new V-shaped steel truss in the floor slab of the second storey.

Installation of the new V-shaped steel truss in the ground floor level.

Context

The seismic retrofit was done in connection with a complete renovation of the retail shop in the ground floor level.

Relevant data

Year of construction	1966
Building use	Shopping center with apartments
Occupancy	PB = 71
Building value	CHF 5,5 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	C
Compliance factor (initial state)	α_{eff} = 0,2
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening, Improving regularity
Year of retrofit	2005
Cost of retrofit	CHF 0,12 million or 2,2% of building value
Engineer	Dr. Deuring + Oehninger AG, Winterthur

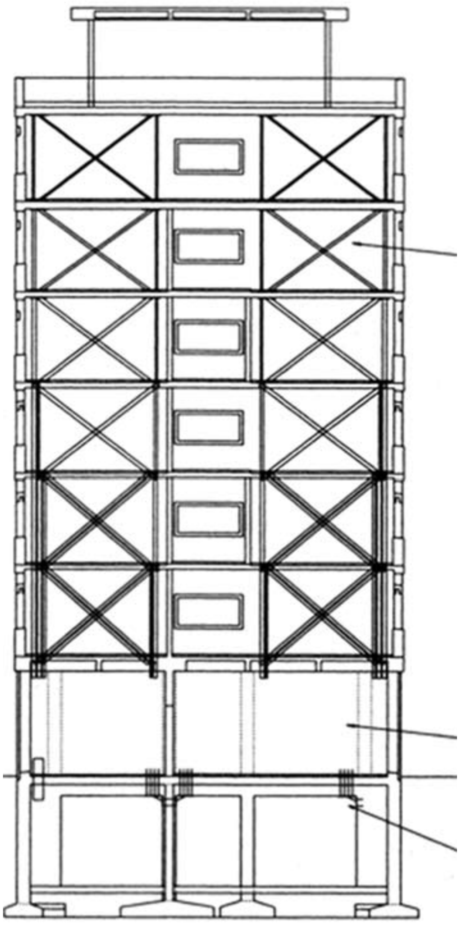
3.20 Friedberg High School in Gossau SG

Initial state

The high rise building of the boarding school of Friedberg High School in Gossau dates to 1961. Bedrooms for the students as well as offices of the school are located in the seven storeys. The building is about 24 m long, 12 m wide and 22 m high. The structural system is primarily out of a reinforced concrete structural wall in the longitudinal direction, masonry walls in the transverse direction and reinforced concrete columns in the facade. The floors are out of reinforced concrete.

Structural weakness

The structural weakness referring to earthquake behaviour are the unreinforced masonry walls in the transverse direction. Because the masonry walls in the ground floor level are interupted, the building exhibits an unfavorable soft ground floor level with large torsional effects.



Retrofit plan

The south side of the masonry walls in the transverse direction from the second through the seventh storey are strengthened with crossed CFRP-strips. On the staircase side, the strengthening with CFRP-strips is limited to the fifth through seventh storeys. From the second through the fourth storeys, a new reinforced concrete wall is concreted against the existing walls. In the ground floor level, new reinforced concrete walls were installed and anchored in the stiff basement. In the longitudinal direction, no strengthening was necessary.

View of the transverse south masonry wall with retrofitting measures: new reinforced concrete wall in the ground floor and strengthening with CFRP-strips in the higher storeys (Borgogno 2001).

Highlights

The diagonal CFRP-strips were secured with newly developed CFRP-shear angles anchored in a prepared drill hole in the concrete deck and secured with counter plates and connecting rods (photo at right). For the vertical CFRP-strips, a sufficient anchorage length is achieved by means of an adhesive bond.

Context

The seismic retrofit plan was done together with other structural preservation measures for the building.

Anchorage of the CFRP-strips with shear angles in the concrete decks.

Strengthening of the masonry walls in the staircase with CFRP-strips.

Relevant data

Year of construction	1961
Building use	Office and dormitory (boarding school)
Occupancy	PB = 25
Building value	CHF 3,7 million
Importance class	IC II
Seismic zone	Zone Z1
Ground type	Medium stiffness
Compliance factor (initial state)	α_{eff} = 0,3 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting strategy	Strengthening, Improving regularity
Year of retrofit	2001
Cost of retrofit	CHF 0,37 million or 10 % of building value
Engineer	Walter Borgogno

3.21 Condominium in Crans-Montana VS

Initial state

The four-storey building in Crans-Montana was originally built as a hotel in the 1950's. In 2004, a conversion to condominiums was done. The floors and the basement are reinforced concrete; the walls are masonry.

Structural weakness

The existing masonry walls were by far not sufficient enough to withstand seismic forces in the highest zone Z3b in Switzerland.

Retrofit plan

The realisation of the new floor layout for condominiums meant that numerous walls needed to be removed. Four slender reinforced concrete walls were constructed as a new bracing system. Following conceptual seismic design principles, the new reinforced concrete walls run continuously from the basement level up to the roof level. The four walls were distributed as symmetrically as possible in plan with the four facade walls.

View of the east facade with the new reinforced concrete walls.

View of the north facade with a new outside reinforced concrete wall.

Construction work at the southeast corner.

Highlights

It was attempted to have the new reinforced concrete walls fit into the architecture of the facades as well as possible.

Context

The seismic retrofit plan was done on the occasion of the conversion of a previous hotel into condominiums.

Reinforcement of a new reinforced concrete wall in the basement.

Foundation of new reinforced concrete walls.

Relevant data

Year of construction	1958
Building use	Condominiums
Occupancy	PB = 6
Building value	CHF 3,6 million
Importance class	IC I
Seismic zone	Zone Z3b
Ground type	A
Compliance factor (initial state)	$\alpha_{eff} = 0{,}2$
Compliance factor (retrofitted)	$\alpha_{int} = 1{,}0$
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	2004
Cost of retrofit	CHF 0,15 million or 4% of building value
Engineers	Gasser & Masserey SA, Crans-Montana

3.22 Hotel in Bussigny VD

Initial state

The Novotel Hotel in Bussigny near Lausanne was built in 1972 as a three-storey building. The hotel is around 75 m long, 16 m wide and 8 m high. Instead of a basement, the building has a crawl space about 1 m high, in which the building's ductwork is routed.

Structural weakness

Originally the building had no bracing system in its longitudinal direction, whether for wind or for earthquake. In addition, the subdivision of the building into four compartments through expansion joints, which ran the whole height of the building, resulted in an unfavorable seismic behavior. Futhermore, the suspension of heavy facade elements made of prefabricated concrete was inadequate. In the building's transverse direction, sufficient walls rest on strip foundations.

End facade on the north side with the new staircase out of reinforced concrete.

End facade on the south side with the new triangular reinforced concrete walls.

Retrofit plan

Both end faces of the building were stabilized through outside bumpers in the longitudinal direction. This was done on the south side by two new triangular reinforced concrete walls and on the north side by a new reinforced concrete staircase. The new bumpers are founded on piles. The existing three expansion joints in the reinforced concrete floors were ceased by expansive mortar. Furthermore, the suspension of the facade elements was strengthened.

Highlights

The bumper on the north side also serves as a new fire escape for improved fire protection. The floor joints were ceased in cold weather producing a prestress pressure between both bumpers with normal building temperature.

Context

The seismic retrofit plan was done together with a general renovation and an extension of the hotel from three to four storeys.

Both new triangular reinforced concrete walls on the south side under construction.

T-shaped steel member for the anchorage of the new reinforced concrete walls in the existing floors.

Relevant data

Year of construction	1972
Building use	Hotel
Occupancy	PB = 60
Building value	CHF 25 million
Importance class	IC I
Seismic zone	Zone Z1
Ground type	B
Compliance factor (initial state)	α_{eff} = 0,12
Compliance factor (retrofitted)	α_{int} = 1,0
Retrofitting strategy	Strengthening, Increasing ductility
Year of retrofit	2008
Cost of retrofit	CHF 180000 or 0,72% of building value
Engineer	E. Molleyres, FM Frank Meylan SA
Architect	Acrobat SA

3.23 Bridge on Simplon Highway A9 VS

Initial state

In its original state, Brunnen Bridge consists of 5- and 10-span continuous girders with an expansion joint at an intermediate column. Both bridge girders are rigidly connected in the longitudinal direction to their respective abutments. In the transverse direction, the bridge girders are fixed on all columns. The total length of the bridge is 270 m. The typical span width runs 16 m over the shorter columns and 26 m over the higher ones.

Structural weakness

In its initial state, the fixed longitudinal bearings at the abutments of each half of the bridge cannot carry by far the seismic forces. The large variation in column heights causes an irregular distribution of transverse stiffness with the result that the very short columns are overstressed in the transverse direction. Furthermore, there is danger of span unseating in the longitudinal direction at the expansion joint of the intermediate column.

View of a portion of the bridge with tall slender columns.

Seismic retrofit with high damping rubber bearings at the abutment.

Retrofit plan

Through the installation of horizontally soft seismic bearings at the abutments and the critical short columns, the longitudinal bearing system was changed from fixed to sliding. The expansion joint at the middle of the bridge was closed.

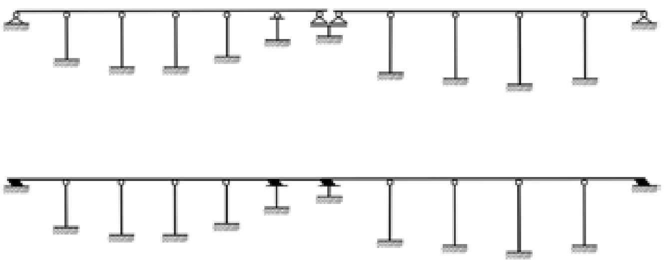
Highlights

The soft bearing system of the bridge with a total of 16 high-damping seismic bearings reduces the seismic forces longitudinally and transversely due to the period shift and due to the higher damping.

Context

The seismic retrofit was done together with other structural preservation measures in the context of a general maintenance of the A9 national highway.

Tightening together both bridge halves at the original expansion joint in the middle of the bridge.



Fixed longitudinal bearing system in the initial state (above) and floating longitudinal bearing system after retrofitting by seismic bearing (below).

Relevant data

Year of construction	1978
Building use	Street traffic
Occupancy	–
Construction value	CHF 7 million
Importance class	BWK II
Seismic zone	Zone Z3b
Ground type	A
Compliance factor (initial state)	$\alpha_{eff} = 0{,}1$
Compliance factor (retrofitted)	$\alpha_{int} = 1{,}0$
Retrofitting strategy	Softening, Reducing seismic action through damping
Year of retrofit	2005
Cost of retrofit	CHF 0,15 million or 2% of construction value
Engineers	VWI Ingenieure AG Truffer Ingenieurberatung AG
Expert	Dr. Thomas Wenk

3.24 Liquid gas tank in Visp VS

Initial state

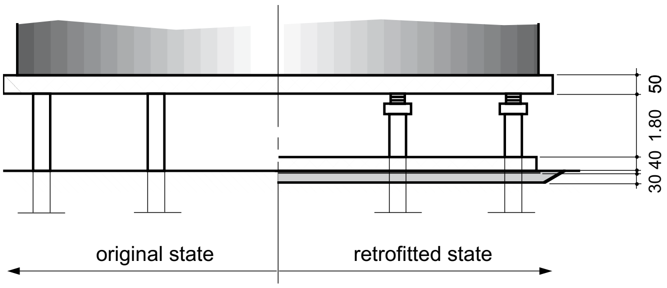
A cyclindrical steel tank with a storage capacity of 1000 tons liquid gas rests on a raised reinforced concrete slab. The steel tank has a diametre of 15 m and a height of 16 m. The slab is laid out on 26 slender reinforced concrete columns. The columns are 2.2 m in height and 50 cm in diametre. They are each founded on separate drilled piles of the same diametre.

Structural weakness

The tank was raised for protection from flood water. In its existing state, the columns and the piles under the tank are very overstressed in bending and shear under horizontal seismic action. The steel construction of the tank is likewise overstressed.

Retrofit plan

Instead of strengthening, the horizontal bearing system will be softened during the installation of 26 special high-damping rubber bearings. As a result of the floating horizontal bearing system (seismic isolation), the relevant fundamental frequency is shifted from 2.2 to 0.5 Hz. The frequency shift as well as increased damping reduce the spectral acceleration and, with it, the seismic forces down to one-third.



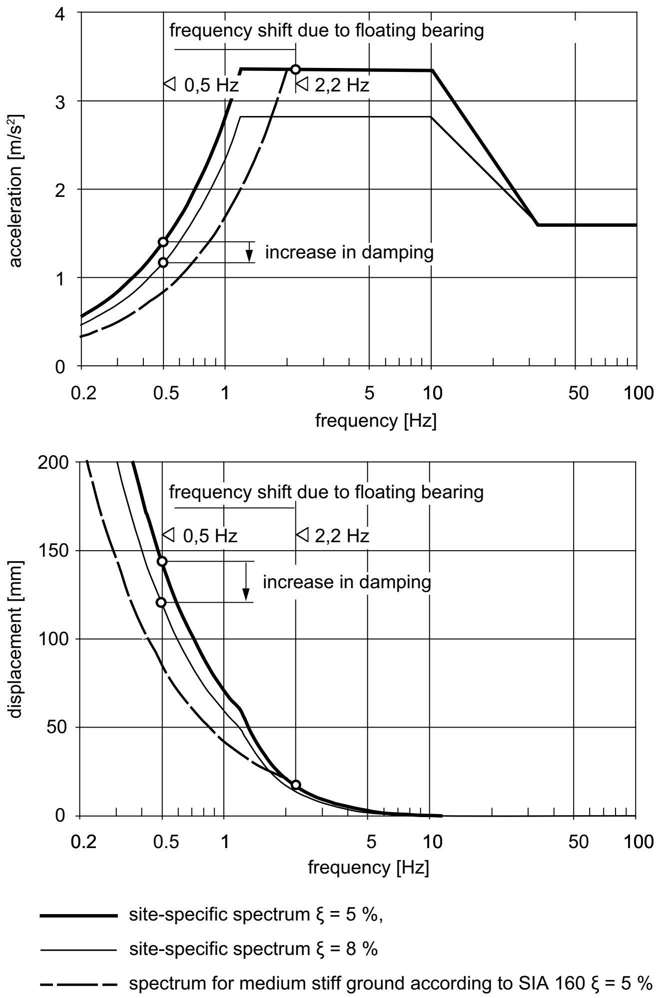
Original state (left) and rehabilitated state (right) achieved through the installation of rubber bearings and an additional lower concrete slab (Bachmann 2000).

Highlights

Through the use of seismic isolation, the seismic forces in the steel tank were so far reduced that the need for an expensive strengthening of the steel construction of the tank could be eliminated. Stair tower and piping have to be checked for the enlarged horizontal oscillations of the tank due to seismic isolation.

Context

The seismic retrofit was done in connection with a risk analysis following the guidelines for major accidents.



Elastic design response spectra of acceleration (above) and displacement (below) with the fundamental frequency before and after the retrofit.

Retrofit by installation of rubber bearings under the liquid gas storage tank.

Relevant data

Year of construction	1980
Use	Storage of liquid gas
Building value	CHF 3 million
Importance class	IC III
Seismic zone	Zone Z3b
Ground type	Site specific, soil dynamic study
Compliance factor (initial state)	α_{eff} = 0,2 (referring to SIA 160)
Compliance factor (retrofitted)	α_{int} = 1,0 (referring to SIA 160)
Retrofitting strategy	Softening, Reducing seismic actions through damping
Year of retrofit	2002
Cost of retrofit	CHF 0,35 million or 12% of construction value
Engineer	KBM Bureau d'Ingénieurs civils SA
Expert	Prof. Dr. Dr. h.c. Hugo Bachmann

3.25 Residential building in Kriessern SG

Initial state

This building is a free-standing multi-family house with two residential storeys, a basement and an attic. The walls are made of unreinforced masonry, and the floors are constructed out of reinforced concrete. The floor plan area measures 9 m by 23 m. The structural system for horizontal action is regular in plan and in elevation.

Proportionality and reasonableness

The investigation of earthquake safety yields a compliance factor of nearly $\alpha_{eff} = 1.0$. Therefore, retrofitting measures are not required independent of the criteria of proportionality and reasonableness of Pre-Standard SIA 2018.

Recommendation for intervention

The existing building can be accepted in its current state as sufficiently earthquake resistant.

Context

The examination of the buiding for earthquake safety was done on the occasion of planning for structural preservation measures.

Relevant data

Year of construction	1960
Building use	Residential
Occupancy	PB = 10
Importance class	IC I
Seismic zone	Zone Z2
Ground type	D
Compliance factor	$\alpha_{eff} = 1,0$
Year of examination	2005
Engineer	Holinger AG

3.26 Laboratory building HPP of ETH Zurich

Initial state

The laboratory building HPP was built in 1969 through 1971 as part of the first building phase of the Hönggerberg Campus of ETH Zurich. The building extends 45 m high over the terrain and has eleven upper storeys and two basement storeys. The floor plan measures 34 m square. The structural system for horizontal action consists of reinforced concrete cores for elevator and stairways extending the entire height as well as other reinforced concrete structural walls. All in all the structural system is nearly regular in plan and in elevation. The floors are reinforced concrete with floor beams in most of the area. Non-structural walls are made of masonry.

Proportionality and reasonableness

The compliance factor α_{eff} just reached the allowable reduction factor α_{adm} = 0,7 for the assumed remaining useful life of 40 years on the basis of the criteria of Pre-Standard SIA 2018. No retrofitting measures were required.

Recommendation for intervention

The existing building can be accepted in its current state as sufficiently earthquake resistant.

Context

The examination for earthquake safety of the building was done on the occasion of planning for structural preservation measures.

Relevant data

Year of construction	1971
Building use	Laboratory and instruction
Occupancy	PB = 300
Importance class	IC I
Seismic zone	Zone Z1
Ground type	C
Compliance factor	α_{eff} = 0,7
Year of examination	2005
Engineer	Basler & Hofmann, Ingenieure und Planer AG

3.27 SIA Office Tower in Zurich

Initial state

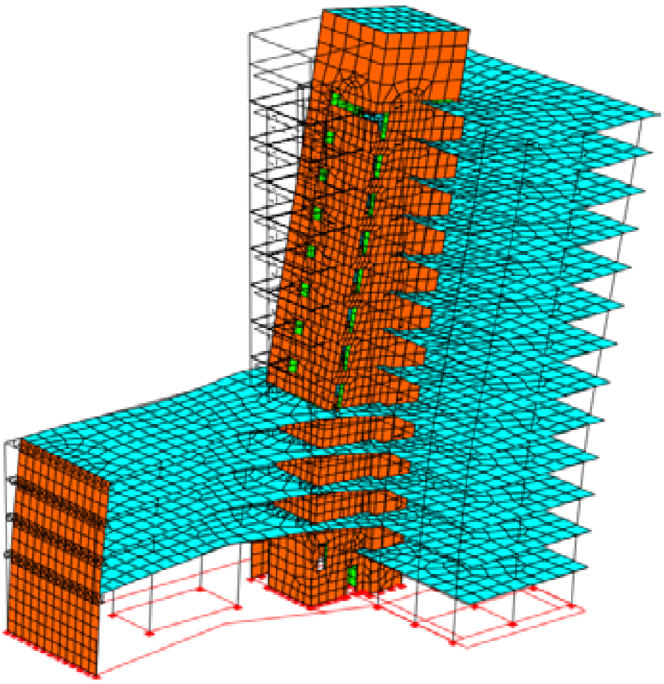
The 40 m high Swiss Society of Engineers and Architects SIA Office Tower was built in Zurich in 1971 as a skeleton frame construction. The bracing for horizontal wind and earthquake forces was provided by an eccentrically arranged reinforced concrete core measuring 8 m by 8 m. During a complete renovation in 2006/07, the original four storey annex building was joined monolithically with the office tower to become a large linked office complex. Because of this, the eccentricity of the bracing system in the lower storeys could be reduced.

Proportionality and reasonableness

Proof of earthquake safety has been demonstrated by response spectrum analysis with a three-dimensional model. With a compliance factor of $\alpha_{eff} > 1{,}0$, consideration of the proportionality of the retrofitting measures is not required.

Recommendation for intervention

After reconstruction, the building is sufficiently earthquake resistant so that no retrofitting measures are required.



Three-dimensional finite element model for the response spectrum analysis.

Context

The examination of the earthquake safety of the building was done on the occasion of planning for the reconstruction conditioned by a change in tenant.

Relevant data

Year of construction	1971
Building use	Office building
Occupancy	PB = 70
Importance class	IC I
Seismic zone	Zone Z1
Ground type	C
Compliance factor	$\alpha_{eff} > 1{,}0$
Year of examination	2005
Engineer	Dr. Lüchinger + Meyer, Bauingenieure AG

> Appendix

A1 Development of the seismic provisions in the standards

Seismic regulations were first introduced in Switzerland in 1970 in the Swiss Standard (SIA 160 1970). With two later Standard revisions in 1989 and 2003, the requirements were strengthened each time. The background reasons were new knowledge in earthquake engineering and in seismology.

According to the actual standards (SIA 260 and following 2003), seismic action to be considered for a structure varies heavily on the dependence on different parametres. The five most important are:

> importance class
> seismic zone
> ground type
> method of construction
> dynamic behaviour of the structure

The combination of these parametres determines the size of the seismic action for the design of a structure. Table 1 shows how these parametres developed and changed in different revisions of the standards.

Tab. 1 > Development of the parametres for determining the seismic action in the SIA Standards

Revision of Standards	SIA 160	SIA 160	SIA 260 and following
Effective date	1970	1989	2003
Number of structure categories	2	3	3
Number of seismic zones	1	4	4
Number of ground types	none	3	6
Number of types of construction	1	5	27
Dynamic behaviour	not considered	considered	considered

The basis for the division into one of the three structure **importance classes** (**IC**) are the average of the occupancy, the potential for damage, the endangering of the environment, and the importance of the structure for emergency managing immediately after an earthquake. Regular residential and commercial buildings are placed in IC I. Buildings with larger gatherings of people (shopping malls, sports stadiums, cinemas, theatres, schools, and churches) as well as buildings of public government are placed in IC II. Essential facilities (so called lifeline buildings) with important life-saving infrastructure functions, such as fire stations, ambulance garages or emergency hospitals, are classified as IC III. The size of the seismic design event is scaled in dependence of the importance class with an importance factor $\gamma_f = 1,0$ for IC I, $\gamma_f = 1,2$ for IC II and

γ_f = 1,4 for IC III. The return period of the seismic design event amounts to 475 years for IC I, 800 years for IC II, and 1200 years for IC III.

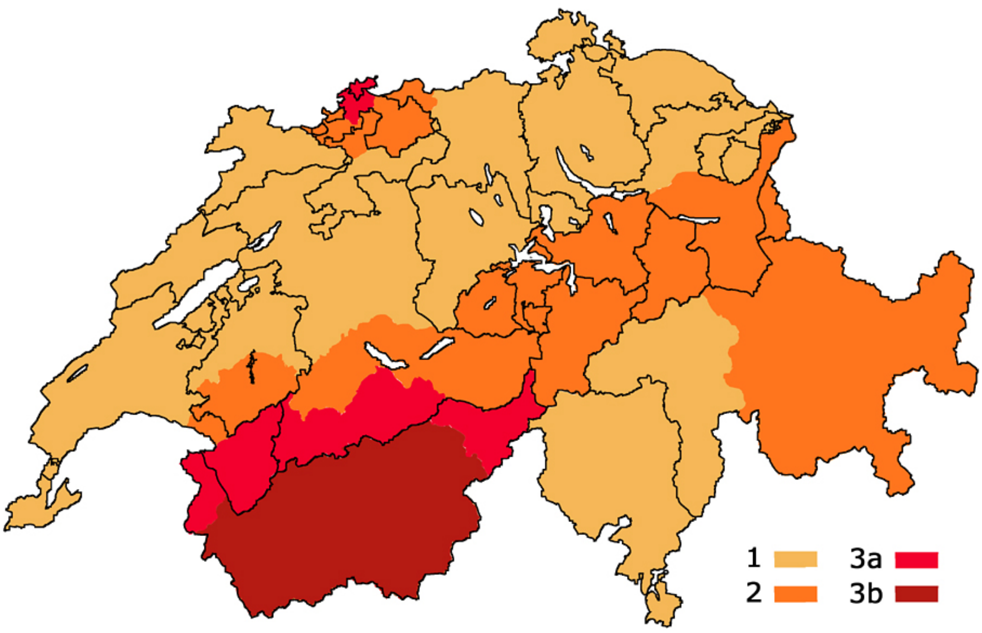
In Standard SIA 160 from 1970, there were two importance classes with an importance factor of 1,4 for the seismic action of the higher IC, meaning for buildings with higher gatherings of people (theatres, churches, hospitals, shool buildings).
The Standard SIA 160 from 1989 distinguished between three importance classes and, with it, made a gradation of seismic forces similar to that in the current Standard SIA 261 (2003).

Today Switzerland is divided into four **seismic zones** (Fig. 12). In the Alps and in the region around Basel the hazard is somewhat higher than in the Jura, the central region or in Tessin. Looking at the whole world, the exposure to earthquake hazard in Switzerland is between low and moderate seismicity. The maximum horizontal ground acceleration for rock (ground type A) totals 0,6 m/s^2 in the lowest zone Z1. It is 1,0 m/s^2 in zone Z2, 1,3 m/s^2 in zone Z3a, and 1,6 m/s^2 in the highest zone Z3b.

In Standard SIA 160 from 1970, there was a uniform, hazard level with a horizontal acceleration of 0,2 m/s^2 applied to the whole of Switzerland. Only in the Canton of Basel, the local authorities prescribed a higher level of 0,5 m/s^2. The Standard SIA 160 from 1989 contained likewise four seismic zones with the identical acceleration values, but with smaller geographical perimetres of the higher seismic zones as in the current Standard SIA 261.

Fig. 12 > Seismic zone map of Switzerland

Standard SIA 261 (2003) divided Switzerland into four seismic zones.



Within a seismic zone, the seismic excitation varies depending upon the local ground conditions at the sites of the structures. Basically, the weaker the foundation, the stronger and low-frequented the seismic excitation. Standard SIA 261 contains five **ground types** from A through E with different seismic action as well as a sixth ground type F for structure-sensitive or organic soils, in which a special site-specific soil dynamic study is performed (Tab. 2).
In Standard SIA 160 from 1970, there were no ground types. Standard SIA 160 from 1989 contained different response spectra for two ground types (stiff ground and medium-stiff ground). For stiff ground with weakly consolidated, post-glacial deposits, a special study would be required for determining spectral values.

Tab. 2 > Ground types in the SIA Standards

Ground types in Standards SIA 160 (1989) and SIA 261 (2003) for determining seismic action.

Classification of ground type SIA 160 (1989)		Classification of ground type SIA 261 (2003)	
Stiff	Rock, compacted gravel and moraine, compacted gravel and sand with soil shear wave velocity over 800 m/s under a covering of loose stone of maximum 10 m	A	Hard rock (e.g., granite, gneiss, quartzite, siliceous flint, limestone) or softer rock (e.g., sandstone, conglomerate, Jura marl, opalinus clay) under maximum 5 m covering of loose stone
		B	Deposits of extensive cemented gravel and sand and/or disadvantaged loose stone with a thickness under 30 m
Medium-stiff	Loose to medium dense layered silt, sand, gravel and medium stiff to stiff clay over 10 m thick layer	C	Deposits of normally consolidated and uncemented gravel and sand and/or moraine material with a thickness over 30 m
		D	Deposits of unconsolidated fine sand, silt and clay with a thickness over 30 m
		E	Alluvial superfical layer of ground type C or D with a thickness between 5 and 30 m over a stiff layer of ground type A or B
Weak	Soft soil out of weakly consolidated post-glacial deposits, as for example limestone or clay of more than approximately 10 m thick layer	F	Structurally sensitive and organic deposits (e.g., peat, limestone, landslide) with a thickness over 10 m

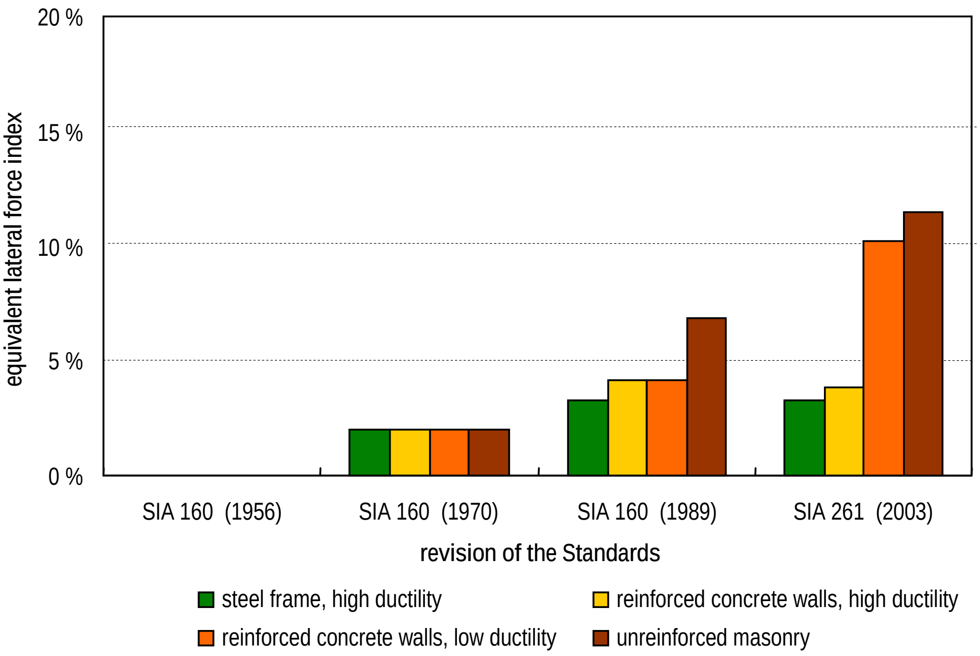
In the current Standard SIA 261 (2003), the difference of the seismic excitation in the low-frequency regions between the ground types within the same seismic zone can be just as big as the difference between the four seismic zones of Switzerland. Thus, for a structure site on loose soil in the lowest zone Z1 the seismic excitation can be the same as for a rock site in the highest zone Z3b.

For the determination of the ground type according to Standard SIA 261 consult the map of ground types on the website of the Swiss Federal Office for the Environment under *www.bafu.admin.ch/erdbeben* and follow the link to the English translation or view the interactive map at > Karte der Baugrundklassen und der Erdbeben-Gefährdungszonen nach SIA 261.

The most important influence on the size of the applied seismic action is from the **method of construction** and the **dynamic behaviour of the structure**. Both of these aspects have had the largest change on the revision of succeeding standards from new knowledge in earthquake engineering.
While the first revision of seismic standards in 1970 produced the same seismic forces for all methods of construction, the difference between the methods of construction in the following revision of standards would take shape thanks to newer knowledge of the behaviour of ductile structural support systems (Fig. 13). Figure 13 shows the comparison size of the equivalent lateral force index, that is to say the relationship of the applied horizontal seismic force to the relevant weight of the building, as a function of the last four revisions of standards and differing methods of construction. As a calculated example, the figure shows a horizontally stiff building in seismic zone Z1 on ground type C with the fundamental period of vibration at the maximum acceleration domain (value at the plateau) of the design spectra.

Fig. 13 > Seismic actions for buildings following revisions of SIA Standards

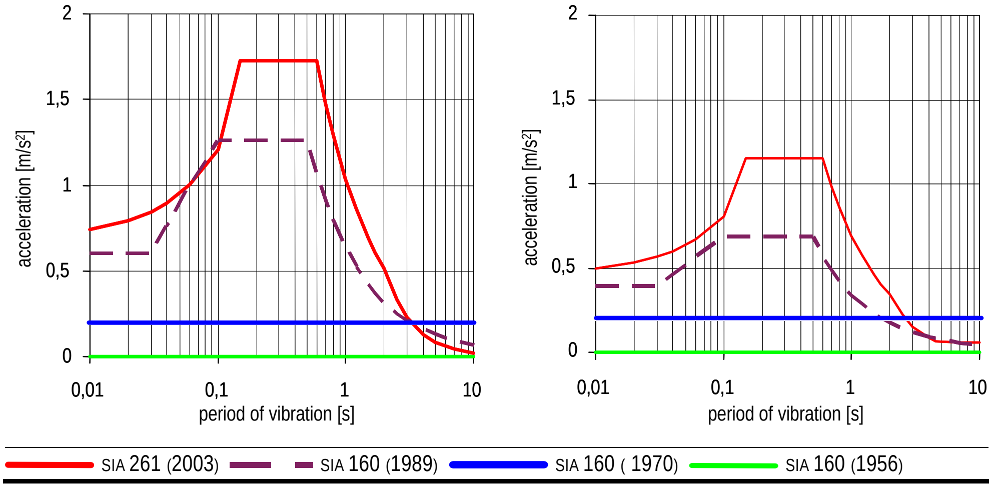
Development of the seismic action of the last four revisions of standards for differing methods of construction represented by the horizontal equivalent lateral force as percentages of the building's weight (equivalent lateral force index) for horizontally stiff buildings in seismic zone Z1 on ground type C.



As further means of comparison, Figure 14 portrays the acceleration response spectra for buildings made of unreinforced masonry in zone Z1 on ground type C of the respective revisions of standards. Figure 14 shows the response spectra for elastic structural behaviour (left) and the corresponding design spectra for unreinforced masonry (right). The design spectra for masonry are reduced compared to the elastic response spectra because load carrying reserves above the nominal resistance due to overstrength and ductility can be considered.

Fig. 14 > Development of the response spectra in accordance with revisions of SIA Standards

Comparison of the acceleration response spectra for elastic structural behaviour (left) and the design spectra for unreinforced masonry (right) respectively in the lowest zone Z1 in ground type C (medium stiff ground) for the last four revisions of standards.



The strong increase of the seismic action in the new standards mainly occured for the period of vibration domain from 0,1 to 2,0 s. This affects primarily horizontally stiff buildings of around one to six storeys. For higher buildings with fundamental periods of vibration over 3 s, the seismic action is more likely lower. Furthermore, unreinforced masonry buildings experience an especially large increase in seismic action, while for ductile construction, respecting seismic design principles, such as ductile steel or reinforced concrete construction, the increase in seismic action stayed relatively low.

A2 Costs of the seismic retrofitting for the collection of examples

The costs of the seismic retrofitting varied quite considerably between the examples. As a comparison, the values of the seismic retrofittings for the 24 examples of the collection are ordered in Table 3 by their decreasing relative costs as a percentage of the value of the structures.

Tab. 3 > Costs of the seismic retrofitting

Values of the seismic retrofitting of the examples ordered in decreasing relative costs as percentages of the value of the structure.

Structure	IC	Zone	α_{eff}	α_{int}	Cost in % of Value of Structure
Cantonal Police Building in Sion VS	III	Z3b	0,2	1,0	29 %
Fire Station in Basel	III	Z3a	0,2	1,0	23 %
Liquid Gas Tank in Visp VS	III	Z3b	0,2	1,0	12 %
School ESC in Monthey VS	II	Z3a	0,15	0,8	11 %
Friedberg High School in Gossau SG	II	Z1	0,3	1,0	10 %
School CO in Monthey VS	II	Z3a	0,16	1,0	7,7 %
Residential Building with Shopping Center in Fribourg	II	Z1	0,5	1,0	7,4 %
Substation in Basel	III	Z3a	0,3	1,0	5 %
Children’s Hospital Aarau	II	Z1	0,1	1,0	4 %
Condominium in Crans-Montana	I	Z3b	0,2	1,0	4 %
Government Building in St-Maurice	II	Z3a	0,17	0,7	3,5 %
Residential and Commercial Building in Sion	II	Z3b	0,2	1,0	3 %
School in Zurich	II	Z1	0,2	1,1	3 %
Radio Station Zurich	II	Z1	0,3	1,0	2,3 %
Residential Building and Shopping Center in Winterthur	II	Z1	0,2	1,0	2,2 %
Bridge on Simplon Highway A9 VS	II	Z3b	0,1	1,0	2 %
Fire Station in Visp VS	III	Z3b	0,4	1,0	1,8 %
EMPA Administration Building in Dübendorf ZH	II	Z1	0,25	1,0	1,5 %
Hotel in Bussigny VD	I	Z1	0,12	1,0	0,7 %
School in Ostermundigen BE	II	Z1	0,24	0,6	0,7 %
Neufeld High School in Bern	II	Z1	0,1	0,5	0,7 %
Auditorium HPH of ETH Zurich	II	Z1	0,25	1,0	0,7 %
Multi-purpose Hall in Oberdorf NW	II	Z2	0,1	1,0	0,5 %
Government Building in Bern	II	Z1	0,1	(1,0)	0,4 %

The range of costs reach from 0,4 to 29 %. The table leads off with three structures in IC III in the two highest zones, in other words, structures with the highest demands on seismic safety in Switzerland. The structures are grouped by IC and seismic zone, the bandwidth of relative costs of the seismic retrofit is reduced to the following values:

> IC III in zone Z3b: 2–29 %
> IC III in zone Z3a: 5–2 %
> IC II in zone Z3b: 2– 3 %
> IC II in zone Z3a: 3,5–11 %
> IC II in zone Z2: 0,5 %
> IC II in zone Z1: 0,4–10 %
> IC I in zone Z3b: 4 %
> IC I in zone Z1: 0,7 %

These wide ranges indicate that the costs are obviously much stronger dependent on the construction constraints of the seismic retrofit in the particular case than from the intensity of the seismic action. The objects with the favorable costs distinguish themselves through locally narrow, limited structural intervention, for example, only closing an expansion joint or adding bracing in only one storey. When new structural elements over the whole height are necessary, the costs quickly rise even in the lowest seismic zone Z1, especially when additional strengthening of the foundation is required.

> Index

Abbreviations

SIA
Swiss Society of Engineers and Architects

Glossary

Importance class (IC)
Systematic characterization of buildings according to Standard SIA 261, for similar danger to people, the importance of the structure for the general public, and the danger to the environment resulting from damage to the structure.

Ductility
Measure of energy dissipation and the plastic deformation capacity of a structural element, expressed for a displacement or deformation quantity as a quotient of maximum value and value at the beginning of the plastic zone.

Compliance factor (α_{eff})
Numerical value of which the measure of an existing structural system satisfies the calculated demand of a newly built system according to current standards.

Individual risk
Measure of the risk encountered by a single person expressed as the probability of being killed per year.

Capacity curve
Diagram of the restoring force of an equivalent single degree-of-freedom system as a function of its relative displacement.

Occupancy
Average number of people who are staying in the structure or in its area of rubble.

Life saving costs
Quotient of the measure of security costs and risk reduction expressed in CHF per saved life.

Deformation capacity
Deformation of structural elements or a structural system, which could be consumed before the structural element or the structural system reaches its nominal failure state.

Proportionality
Guarantee of intervention efficiency to the reduction of total risk with limitation of individual risk.

Reasonableness
Guarantee of intervention efficiency with qualified limitation of individual risk.

CFRP-strip
Carbon fibre reinforced polymer strip

Figures

Tables

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