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Seismic retrofit of an existing fire station to ensure its critical emergency response function

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ABSTRACT: Certain elements of a country's infrastructure, which are critical to the region's response to a catastrophic event, must continue to function in the aftermath of an earthquake. This applies not only to the roads and bridges which must continue to facilitate the movement of affected people and emergency services, but also to the buildings which will be vital to relief efforts. Hospitals must provide care to the injured at a time when the number requiring care suddenly multiplies; police stations must be centres of stability and order when chaos suddenly threatens; and fire stations must continue to fulfill their role in preventing the spread of any fires which will inevitably follow a serious seismic event, and in providing emergency search and rescue services. Very often such buildings, perhaps built many years ago, were not constructed to be earthquake proof, arising in the need for works to be carried out retrospectively in order to ensure a building's survival and usefulness following an earthquake. A project to make one such critical structure "earthquake-proof" is described: the central fire station of the city of Basel in Switzerland. Following analysis of the building, its environment and the local seismic threat, it was decided, rather than simply strengthening the structure, to seismically isolate it from the ground beneath and around it. This was achieved by separating the entire structure from its foundations (by cutting horizontally through its basement walls and pillars) and resting it on elastomeric bearings which would allow less violent movements of the building and dissipation of energy in a seismic event. This approach also required the ground next to the building to be removed down to the level of the new bearings, to allow the structure to move freely without resistance from the soil. This was of particular relevance for the fire station's many entry/exit points, which thus required the installation of expansion joints to bridge the resulting gap for the exiting fire trucks. Following the successful completion of the project, the fire service of Basel is now considerably better prepared to serve the city in the aftermath of its next major seismic event.

1 INTRODUCTION

Many countries, even in relatively seismically stable regions of the world, are subjected to the risk of earthquakes, even if these are less frequent and generally less severe than those in more seismically active parts of the world such as the Pacific ocean "ring of fire". Although Europe is not widely recognised as a seismic hotspot, a number of the continent's countries are subjected to significant earthquake risks, as shown in Figure 1. Switzerland, situated in the heart of western Europe, is a good example, and in particular the city of Basel on the borders to both France and Germany, which was devastated by an earthquake in the year 1356 (Figure 2).

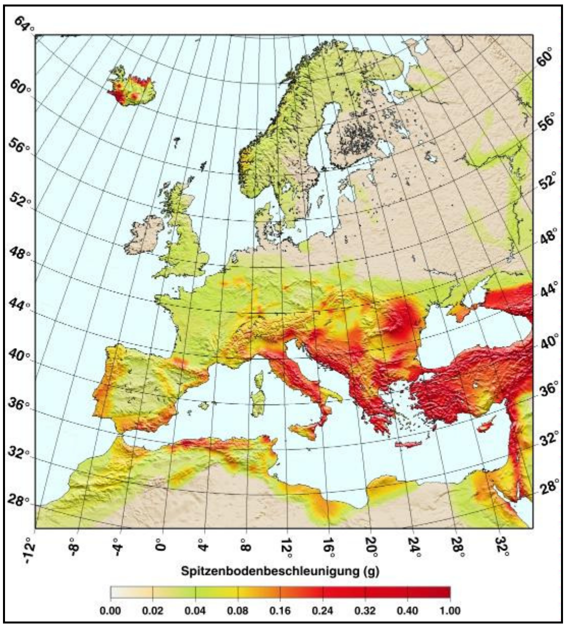

Figure 1. Map of Europe showing seismic risk. [Deutsches GeoForschungsZentrum (2008)]

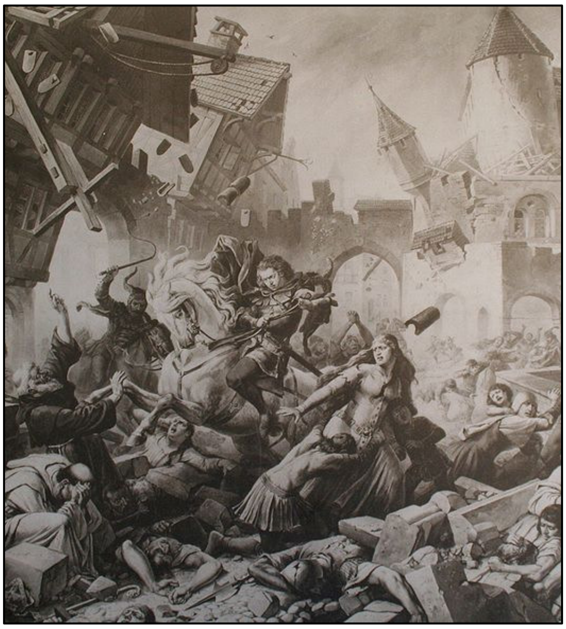

Figure 2. Depiction of the devastation caused to the city of Basel by an earthquake in the year 1356 (Karl Jauslin, 1842-1904)

It is estimated that a severe earthquake, of the scale of that which struck Basel in 1356, would today cause between 500 and 5,000 deaths, and up to 100 billion dollars worth of damage to the city [PLANAT (1999)]. A key element of the city's planning for such an event involves ensuring that emergency services, and in particular its fire brigade, will be able to fulfil their critical functions in the aftermath of a serious earthquake. The main building of the city's fire brigade (Figure 3), however, was itself considered to be at risk of collapsing in even a relatively minor earthquake, giving rise to the need to make it "earthquake-proof". The resulting project to modify the structure to achieve this is described below, with particular focus on the bearings and expansion joints required to enable the building to vibrate, and thus avoid destruction, during a strong earthquake.

Figure 3. The central fire brigade building of the city of Basel, Switzerland

2 BACKGROUND TO THE PROJECT TO ADAPT BASEL'S CENTRAL FIRE BRIDGE BUILDING TO WITHSTAND A SERIOUS EARTHQUAKE

A national Seismic Risk Mitigation Program was established by the Swiss authorities in 1999 to assess the risks of earthquakes affecting the country, and to mitigate these as appropriate. The goals of this primarily include: protection of the population; prevention of catastrophe and distress (in order to minimise resulting costs and prevent political destabilisation); protection of the environment and cultural heritage; and protection of national property. The program consists of 18 coordinated actions in the fields of legislation, hazard assessment, data acquisition, buildings and systems strengthening, education and information, emergency management and research. One of these actions relates to the seismic safety of existing federal buildings and structures, under which the seismic safety of such buildings would be reviewed, and according to priority criteria for risk reduction, selected structures would be modified if necessary in order to achieve acceptable earthquake resistance [PLANAT (1999)].

Among these federal buildings must be considered fire stations, which must continue to fulfil their role in preventing the spread of any fires which will inevitably follow a serious seismic event, and in providing emergency search and rescue services. Destruction of the service's headquarters by the very event whose impacts must be mitigated would seriously inhibit an effective response. The fire station of the city of Basel was determined to have a so-called "compliance factor" according to the Swiss standard SIA 2018 of only 0.2 – meaning that the earthquake resistance of the building amounted to only 20% of that of an equivalent new building constructed in accordance with the standard [Bachmann (2009)]. This made the seismic retrofitting of these key buildings critical to the city's preparedness for a major seismic event.

3 APPROACH TO THE PROJECT

3.1 The existing structure

The central fire brigade building of the city of Basel, originally constructed in 1942, has a plan area of 44m x 15m. Its vehicle hall dominates the ground floor, with 11 entry/exit doors on each side of the building. Upper floors are used for living quarters, administration and storage. Having been constructed before the advent of seismic engineering as it is practised today, it is not to be expected that the building was originally built to modern standards of seismic protection. From a seismic analysis viewpoint, the building was determined to have a "soft storey" on the ground floor, and it was established that various critical structural members would not be capable of withstanding a significant earthquake. It was therefore concluded that there existed a need for works to be carried out retrospectively in order to ensure the building's survival and usefulness following an earthquake.

3.2 Approaches for improving a building's ability to survive an earthquake

A number of strategies may be considered where an important building is at risk from earthquakes [BAFU (2008)]:

- Improve regularity / symmetry;
- Strengthen;
- Increase ductility (i.e. capacity for plastic deformation);
- Install flexible mountings (i.e. reduce stiffness);
- Reduce effect of earthquake by damping;
- Reduce mass of structure;
- Change use of structure.

The choice of strategy, or combination of strategies, will depend on the circumstances and construction of any individual structure, its functions, its environment and the local seismic threat.

3.3 The selected approach for the fire brigade building

Following analysis of all relevant factors, it was decided that the most suitable approach would consist of "base isolation", i.e. seismically isolating the building from the ground beneath and around it, in a combination of the strategies "weaken" and "reduce effect of earthquake by damping". This could be achieved by separating the entire structure from its foundations (by cutting horizontally through its basement walls and pillars) and resting it on a network of seismic elastomeric and sliding bearings which would allow less violent movements of the building and dissipation of energy in a seismic event. This approach also required the ground next to the building to be removed down to the level of the new bearings, to allow the structure to move freely without resistance from the soil. This was of particular relevance for the fire station's 22 vehicle access points, which thus required the installation of expansion joints to bridge the resulting gaps for entering/exiting fire trucks. This approach also required the separation of the building from neighbouring buildings at both ends, with the shortening of adjacent buildings by between 15 cm and 18 cm.

Such a system of "base isolation" will have the effect, in a strong earthquake, of softly counter-acting the horizontal movements of the building relative to the ground which supports and surrounds it, leaving the building in the same position it has always been while the surrounding soil vibrates violently. The reduced vibrations thus transmitted to the building will not cause serious damage, ensuring the ongoing functioning of the fire service.

A more conventional strengthening of the structure was not favoured for several reasons:

- at least four vehicle entry/exit doors would have had to be blocked by new wall sections, significantly reducing the station's fire-fighting capacity;
- the upper floors of the building would have had to be strengthened;
- the foundations would have required expensive strengthening to transfer the seismic forces acting on the strengthened building to the surrounding soil; and
- a high degree of disturbance, and high costs, would have resulted from the temporary moving of the service to another building while works were carried out.

The "base isolation" approach was therefore deemed most suitable in the circumstances.

The bearings for the system were designed to reduce the fundamental structural frequency from about 3 Hz to about 0.3 Hz, corresponding to an increase in the fundamental period from about 0.3 s to 3 s. As a result of the frequency shift and increased damping, the acting seismic forces could be reduced to about one-tenth of those effective without base isolation, corresponding to an increase of the (force-based) seismic safety by a factor of approximately 10 [Bachmann (2009)].

4 IMPLEMENTATION

The main upper part of the building with its mass of approximately 4,000 tonnes was completely separated, and thus isolated, from its basement and foundations, by horizontally cutting through all support walls and pillars at a depth of approximately 1 m below ground level, as shown in Figure 4. Then seismic bearings, sliding bearings and expansion joints were placed, each to fulfil its own individual function as described below.

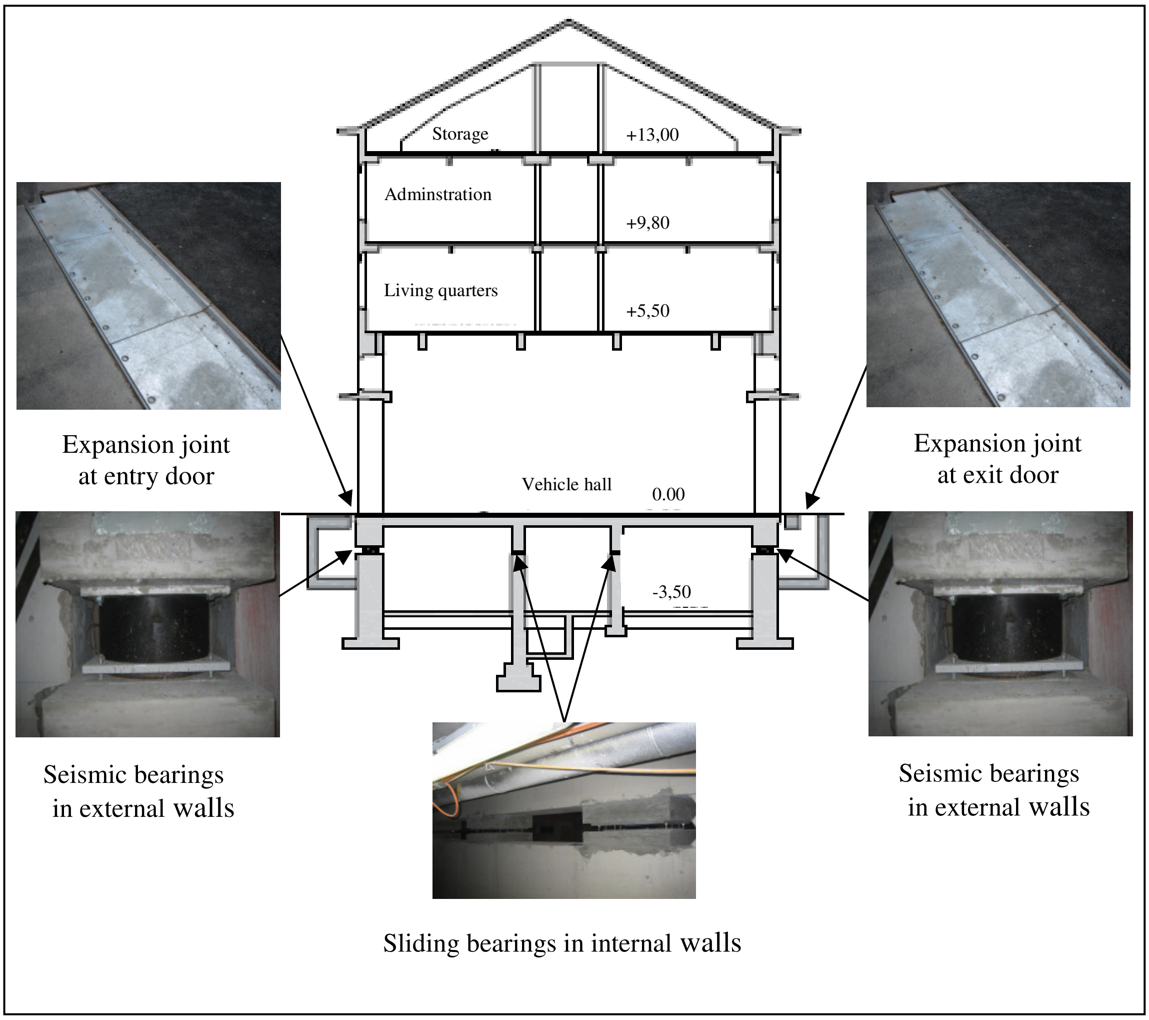

Figure 4. Section through building, showing introduced bearings and expansion joints

4.1 Seismic bearings

Seismic bearings, which during an earthquake will control and determine the movement of the building relative to the supporting and surrounding soil, were placed beneath the building's main load-bearing elements (the columns at the perimeter of the building), as shown in Figure 5. These bearings primarily consist of cylindrical elastomeric blocks which are internally reinforced by a series of horizontal steel plates (as illustrated in Figure 6), and are equipped with external steel anchoring plates.

The bearings allow very little vertical deformation, which is important for the building above, but can through shear deformation of their elastomeric layers facilitate significant horizontal movements. This elastic deformation, much "softer" than the sudden jerking movement which would result in the absence of these bearings, is key to the effectiveness of this type of bearing in a seismic situation. The performance properties of the bearings can be modified by adapting their physical dimensions and chemical and mechanical properties (such as shear modulus and damping), with their hysteresis and damping behaviour designed to suit the calculated requirements of the structure during a seismic event.

Figure 5. Seismic bearing installed beneath pillar at perimeter of building

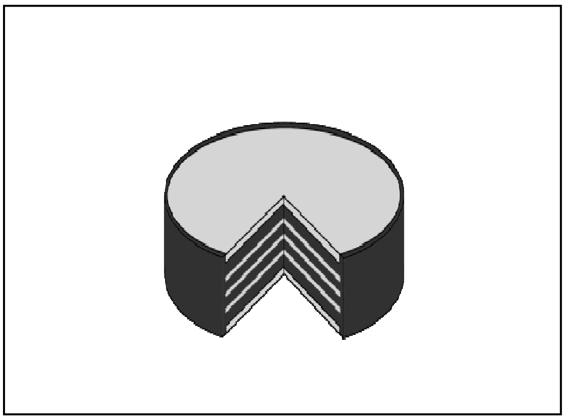

Figure 6. Schematic of reinforced elastomeric block at centre of bearing, with segment cut out

To avoid differential settlements of one part of the building relative to an adjacent section during sequential installation of the seismic bearings, which could arise due to the 2.5 mm compression to be expected in each bearing, a flat hydraulic jack was inserted beneath each seismic bearing, and used to pre-compress the bearings to 95% of the stress which would apply under permanent loading. These flat jacks, which can also be seen beneath the bearing in Figure 5, were injected with quick-hardening cement grout to achieve and maintain the appropriate height, and permanently left in the structure.

4.2 Sliding bearings

The sliding bearings were introduced beneath the open central area of the ground floor, which has no walls or pillars above, and thus serve to transfer the weight of the floor slab and vehicles to the longitudinal walls beneath while allowing the floor slab to move as determined by the seismic bearings at the perimeter. The installation of a row of sliding bearings in one internal basement wall is shown in Figure 7. The bearings allow sliding movement in all horizontal directions, resisting only downward forces. Each bearing consists of a reinforced elastomeric bearing, similar to that shown (with corner cut out) in Figure 8, with a PTFE sliding surface on the upper surface, positioned between two steel anchoring plates, one of which has a stainless steel sheet welded to its lower surface as a sliding partner for the block's PTFE surface.

Figure 7. Sliding bearings inserted in internal basement wall

Figure 8. Schematic picture of an elastomeric bearing (without steel anchor plates above and below) with one corner cut away

4.3 Expansion joints

In order to enable the building to move relative to its basement walls on the bearings described above, the backfill to the basement walls had to be removed down to the level of the newly installed bearings. Any soil against the wall above this level would resist the building's movement, negating the effect of the introduced bearings. This required the construction of subsurface walls to maintain the shape of these new recesses (as shown in Figure 4). The gap at the top of each recess will vary during an earthquake as the building moves relative to the adjacent paving, but it was not possible to leave this gap open, as fire brigade vehicles need to cross the gaps in entering and leaving the building every day. Therefore sliding plate expansion joints were installed at ground level along both long sides of the building, as shown in Figures 9 to 11.

Figure 9. Installation of expansion joint

Figure 10. Installed expansion joint at vehicle exit

Figure 11. Vehicle exit point after completion of works, showing new stainless steel expansion joint

4.4 Other measures

Services (cables, ducts, pipes etc) also had to be fitted with expansion sections to prevent these becoming severed during movements of the building – particularly important for the communications cables that would be critical to the proper coordination of emergency response efforts. The newly created gaps between the fire station and the adjacent building on either side were also blocked at the building facades to prevent the ingress of water, animals, etc.

5 CONCLUSIONS

This was the first such seismic upgrading of an existing building north of the Alps, and compared to a conventional strengthening, the costs were significantly lower. Moreover, the resulting seismic safety is considerably higher and the vulnerability to a severe earthquake significantly lower than would have been achieved by conventional strengthening [Bachmann (2009)]. As an additional (and important) benefit of the chosen approach, the impact on fire service operations could be minimised, saving the effort and expense of temporarily relocating fire brigade operations to another building while the works were carried out, and avoiding any long-term reduction in the fire-fighting capacity of the station. The role played by the bearings and expansion joints of two leading suppliers was central to the solution, and thanks to these and the clever design of the responsible seismic engineer, the fire service of Basel is now considerably better prepared to serve the city in the aftermath of its next major seismic event.

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