Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 30 (1978)

Artikel: Structural behaviour of the damaged building during the Friuli earthquakes between May 6 and September 15, 1976

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DOI: https://doi.org/10.5169/seals-24182

STRUCTURAL BEHAVIOUR OF THE DAMAGED BUILDING DURING THE FRIULI EARTHQUAKES BETWEEN MAY 6 AND SEPTEMBER 15, 1976

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ABSTRACT

Between May 6th and September 15th, 1976, Friuli was hit by 18 earthquakes with a magnitude of $M \leq 3.8$. The expansion of structural damage caused by the further strong shocks in September was investigated in those buildings (1) which had been closely examined during the first stay in the earthquake area (2).

Additional building damage depended to a large extent on behaviour during the first earthquake load as well as on the different kinds of repairs carried out in the meantime.

ABSTRAIT

Entre le 6 mai et le 15 septembre 1976 le Friaul a été ébranlé par 18 secousses sismiques de magnitude $M \leq 3.8$. Les expansions des dégâts causés aux bâtiments par les séismes forts en septembre ont été examinées aux édifices bien connus à l'occasion de la première investigation dans la zone sismigue.

Les dégâts additionels causés aux bâtiments dépendaient considérablement du comportement pendant le premier chargement sismique ainsi que des différentes mesures de réparation réalisées entre-temps.

AUSZUG

Zwischen dem 6. Mai und dem 15. September 1976 wurde das Friaul von 18 Erdstössen mit Magnituden von $M \leq 3.8$ betroffen. Die Ausweitung der Bauwerksschäden infolge der weiteren, starken Erdbeben im September wurden an den Bauwerken untersucht, die bereits nach dem Erdstoss vom 6. Mai 1976 sehr genau bekannt waren.

Die zusätzlichen Gebäudeschäden waren in sehr starkem Masse vom Bauwerksverhalten während der ersten Bebenbelastung wie auch von den in der Zwischenzeit durchgeführten unterschiedlichen Reparaturmassnahmen abhängig.

1. BACKGROUND

On May 6th, 1976, the Friuli region of Northern Italy was hit by a severe earthquake (Magnitude M = 6.5, measurement of energy released). The epicentral intensity I_o reached the IX to X mark on the XXII-part MSK Scale (Medvedev-Sponheuer-Karnik). This shock had a devastating effect on the buildings in the area.

At the beginning of June 1976, a group of Swiss engineers visited the damaged area. The results of their investigations and the evaluation of the knowledge accumulated is contained in an extensive report (3) with an amply documented description of damage. The geophysical characteristics of the earthquake, the causes of building damage and the behaviour of various building parts under earthquake load have been described in a further paper (2).

A considerable number of aftershocks followed the May 6th earthquake. Within the first two months, 150 aftershocks with epicentral intensities I_o = IV (MSK) were observed.

On September 11th, 1976, after a long period of relative calm, the area was hit by a further earthquake with an epicentral intensity of VII (MSK). This damaging earthquake was exceeded on September 15th by two further strong shocks with intensities almost equal to that of the May 6th earthquake. The earthquake at 4.00 a.m. reached an intensity of VIII (MSK) and that which followed, just after 10.00 a.m., IX (MSK). In order to supplement the impressions gained during the first damage investigations, the area was revisited after the two September earthquakes.

During the second stay in the Friuli earthquake area (1), which lasted from Friday, September 24th until Sunday, September 26th, 1976, the following aspects were investigated and evaluated:

- the process of damage expansion on previously damaged structures,
- the effects of various repair measures on the behaviour of buildings during renewed earthquakes.

In order to distinguish the damage and destruction caused by the two series of earthquakes of May and September from each other, only those buildings were examined which had been closely observed during the first stay. Almost all of the medieval buildings in the centres of the villages and towns were so badly destroyed by the May earthquake (see also (4) that inspection for further damage was pointless.

2. BEHAVIOUR OF PREVIOUSLY DAMAGED STRUCTURES DURING FURTHER STRONG MOTION EARTHQUAKES

At first glance, it seemed that all the buildings left standing after the May earthquake had been completely destroyed by the severe shocks in September. In particular, many houses in the centres collapsed, though there were only a few deaths since the majority of the population was living in tents and mobile homes.

Only a small part of the structural damage studied can be attributed with certainty to any one of the large number of shocks. Already during the first field trip, building damage was analysed which, apart from the first strong shock, had been subjected to a series of aftershocks with intensities up to I_o = VII (MSK).

Earthquakes of this force can cause noticeable damage to intact structures (see description of damage of the seismic intensity scale MSK 1964). Previously damaged and therefore weakened building elements are strained to an even greater extent by such earthquakes. After the strong earthquakes of September 11th and 15th, 1976, the investigations were further handicapped by this uncertainty. It is, therefore, apparent that the comparison of the two investigations cannot establish in detail to what extent the further damage was caused by the numerous weaker aftershocks or by the three strong shocks of mid-September. Various observations and information obtained from the inhabitants themselves showed, however, that most of the further destruction was caused by the severe earthquakes and that the influence of the aftershocks, in contrast, can be ignored. It has, therefore, been assumed in the following conclusions that the changes observed during the second stay can be attributed in the main to the strong earthquakes of September 11th and 15th.

2.1. Behaviour of Unchanged Structures

Buildings were affected to very different extents during the first earthquake. Some of the buildings, because of their construction type, suffered no obvious or, at the most, light damage, while others were widely destroyed to the point of partial or total collapse. In any event, damage always results in a weakening of the structure and altering of the vibration behaviour and, therefore, less satisfactory behaviour under renewed earthquake stress. In most cases, the structural response under further earthquakes will be higher (Figure 21). For the observation of damage expansion, a series of buildings were examined which had remained unchanged after the first earthquake.

The buildings which were undamaged or which suffered only minor plaster cracks, showed no further damage or, at the most, single wall cracks. Their supporting structure withstood this earthquake load and can be considered sufficiently earthquake-proof against similar earthquakes. The building with severely cracked brick walls suffered in most cases even more masonry damage, due to their weakened condition (Figures 1 and 2).

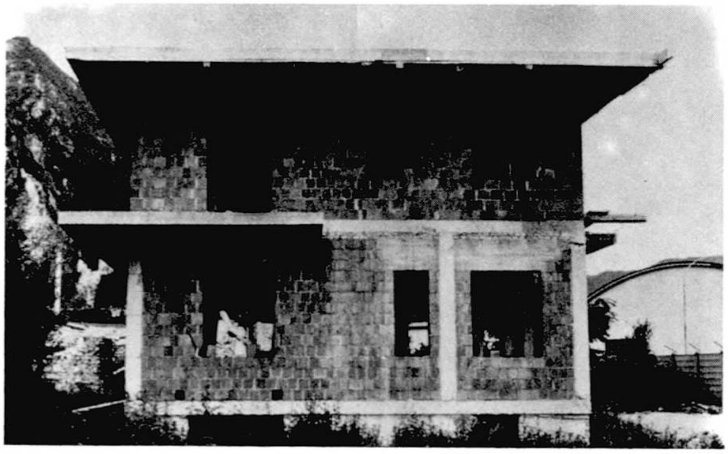


Figure 1: (after May 6th): Uncompleted building in Gemona with groundfloor open on three sides and living floor above. The supporting framework of the groundfloor consists of reinforced concrete columns, partitioned on one of the narrow sides by brick walls. The upper floor is exclusively brick. Due to the earthquake load, the building rotated around the partitioned transverse wall in the groundfloor. The fixing points of the columns were badly damaged in the cellar and groundfloor ceilings. The brick walls on the transverse side on the groundfloor were slighthly cracked: the upper floor remained undamaged.

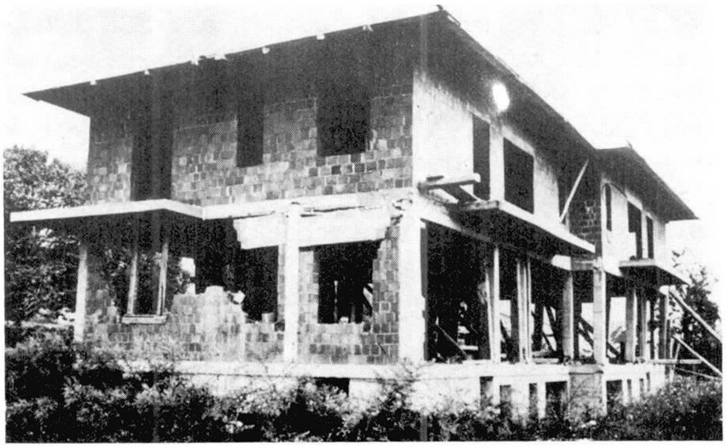


Figure 2: (after September 15th): Uncompleted building in Gemona after renewed earthquake stress. The reinforced concrete columns in the groundfloor were completely destroyed at their fixing points,connection being maintained by the reinforcement only. The massive wooden struts in the groundfloor saved the building from colapse during the second strong earthquake. The already damaged brick wall in the groundfloor was additionally strained due to the strenghtening effect of the wooden struts in the open groundfloor area. The wide brick window jamb was broken out and the reinforced concrete window supports shaken from their rests.

In the case of skeleton structures, this damage could lead to overstrain and, therefore, to damage to the supporting structure. Also badly cracked masonry in non-structural walls means a deterioration of the carrying capacity and a greater danger of building collapse. The carrying capacity was also considerably lessened through the destruction of energy-absorbing building parts such as mortar joints (Figures 3 and 4), whereby the structure experienced reduced damping and therefore suffered greater deformation under renewed earthquake stress.

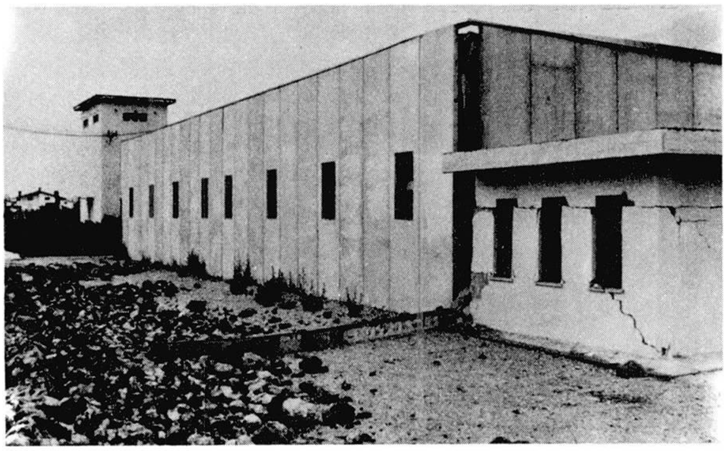


Figure 3: (after May 6th): Prefabricated shed with brick annex in Gemona. The supporting framework of the shed is undamaged. The concrete elements of the side wall, on the other hand, were slightly caved in by the impact of the rigid annex. The plastic material of the wall joints was torn by the large deformation. The roof of the annex was shorn off and pushed over at window level by the impulse load of the impact due to insufficiently wide joints.

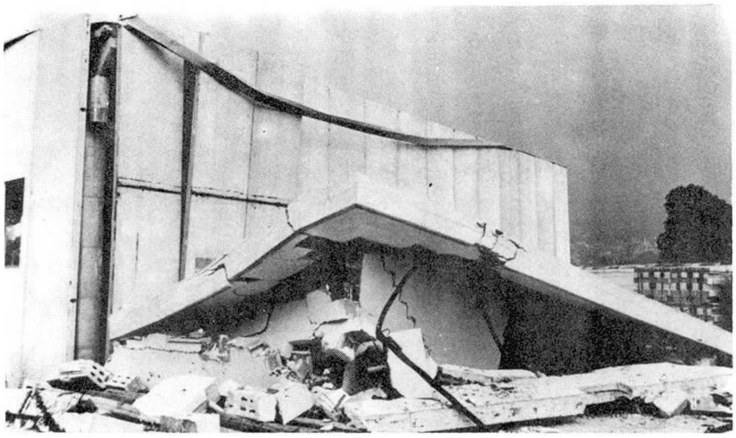


Figure 4: (after September 15th): Prefabricated shed with collapsed annex. The renewed earthquake load caused damage of the supporting framework of the shed at the fixing points of the columns and rests of the bars. The façade slabs of the side wall were severely caved in by the renewed impact: the annex itself collapsed. The increased displacement, as compared with the first earthquake, can be traced back to the reduced structural rigidity due to the destruction of one of the concrete block walls.

Those buildings with badly destroyed brick walls or damage to the supporting structure showed a greatly reduced carrying capacity under renewed earthquake load. The buildings experienced further extensive deformation of the damaged parts which often led to local collapse (Figures 5 and 6) or to the collapse of the entire building (Figures 7 and 8).

Figure 5: (after May 6th): Residential building with workshop near Artegna with a reinforced concrete cellar and two floors in concrete blocks. The side walls by the entrance incurred gaping X-shaped diagonal cracks due to the high shear stress. These cracks led to partial collapse of the masonry. The highly strained window jambs on the longitudinal façade were badly cracked.

Figure 6: (after September 15th: Residential building with workshop near Artegna after renewed earthquake stress. The side wall in the middle floor collapsed under further earthquake load. The door and window jambs on the longitudinal walls shattered and partially collapsed. The shear resistance of these concrete block walls was minimal due to failure of the mortar joints to prevent the layers from shifting.

Figure 7: (after May 6th): Residential building with shop near Artegna. Reinforced concrete frame building with brick partitioning in the two upper storeys In the groundfloor, open on three sides, only the rear longitudinal wall and the staircase are braced. The destruction was concentrated on the groundfloor were a rotating motion of approximately 40 cm maximum displacement occured around the staircase core. The brick walls of the staircase were badly destroyed, while those of the upper floors remained undamaged.

Figure 8: (after September 15th): Wreckage of the residential and business house near Artegna. The groundfloor of the building collapsed during the earthquake of September 11th. Through the impact, the undamaged living storeys also collapsed. The destroyed fixing points of the reinforced concrete columns in the groundfloor as well as the cracked brick walls of the staircase were not enough to carry the renewed strong earthquake stress. The experts had hoped, despite the doubts of the owner, to be able to repair the building.

2.2. Behaviour of Repaired Buildings

After the first strong earthquake, many of those buildings with only minimal or light damage were repaired. Priority was given to those buildings urgently required to keep life-lines open, such as the hospital in Tolmezzo, as well as to industrial and trade buildings in order to resume production and secure employment. The reconstruction work was interrupted by the September earthquakes, thus according the opportunity of judging the merits of the various repair measures and to plan further reconstruction from the standpoint of a threat of further strong earthquakes.

The nature of the repair work was, corresponding to the variety of building types and earthquake damage, very diverse. Therefore, large differences, corresponding to the measures taken, were to be seen after renewed earthquake stress.

2.2.1. Surface Repairs:

Façade and plaster cracks, and even small masonry cracks, were superficially repaired by patching up the plaster and repainting or repapering the walls. Such surface repairs, however, only covered up the weaknesses produced by the cracks in the masonry. Under renewed earthquake load, the same kind of façade damage occured and, due to the existing weakness, the most extensive damage was to be found where the masonry cracks had not been repaired.

2.2.2 Restoration:

Where damage was limited to only a part of the supporting structure or to cracked brick walls, that part was restored as far as possible to its original condition (Figure 9). The object was not only to make the structure reusable but also to reestablish the original carrying capacity against earthquake load. These measures were not intended to improve the carrying capacity, since the existing protection against earthquakes was considered adequate. Naturally, the renewed earthquake load was concentrated on the same building parts and the same damage occured (Figure 9). The repair work which had been undertaken, however, did have the effect of preventing more extensive destruction and offered, therefore a sufficient protection against collapse.

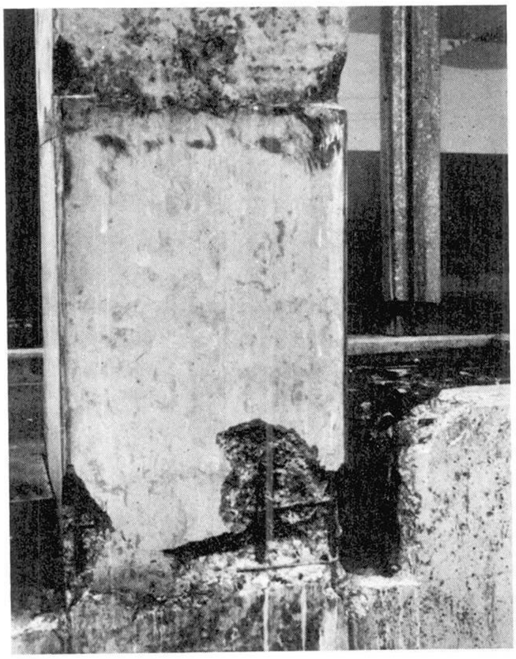


Figure 9: (after September 15th): Foot of a column in the Fantoni furniture factory in Rivoli di Osoppo. By repairing the cracked column foot it was hoped to restore the original carrying capacity. The renewed earthquake load caused the same damage as the first shock, the repaired fixing points of the columns were again cracked and the concrete crumbled in the most highly stressed areas.

2.2.3. Improvement of the Carrying Capacity:

In many cases, an attempt was made to improve the carrying capacity of those structures which were extensively damaged during the first earthquake and which remained unusable for a long period due to complicated repair work. By doing so, the danger of collapse or material loss due to unusability caused by renewed earthquakes should be reduced. The carrying capacity of a structure can be improved in various, distinctly different ways ,which can be applied either single or combined.

The increase in the carrying capacity of the most highly strained building parts results in an increased resistance to renewed earthquake load. This increase in carrying capacity can be attained by replacing the supporting structure with more solid material. In most cases, however, an enlargement of the cross-section of the building parts is a more obvious solution (Figure 12). At the same time, though, the rigidity behaviour is changed and a renewed earthquake will, therefore, put other building parts under a heavier strain.

By altering the vibration behaviour on the other hand, the strain on individual building parts can be changed and heavily strained building parts can be relieved at the expense of other less highly strained parts. Apart from the damping of the structure (see Figures 3 and 4), it is the rigidity and mass behaviour of the structure which above all strongly influence the vibration capacity under earthquake load. Through the walling up of openings in the rear wall of a curved building (Figure 10), its rigidity behaviour was fundamentally altered. Hence, the vibration capacity of the building was so improved that the building parts which had been most strained during the May earthquake suffered no damage during the renewed shocks. Accordingly, the repairs that were made considerably contributed to the improvement of the carrying capacity. The improvement of the vibration capacity provides the most reliable protection against new earthquake damage and makes it possible to achieve optimal strengthening taking the construction type and building material used into consideration.

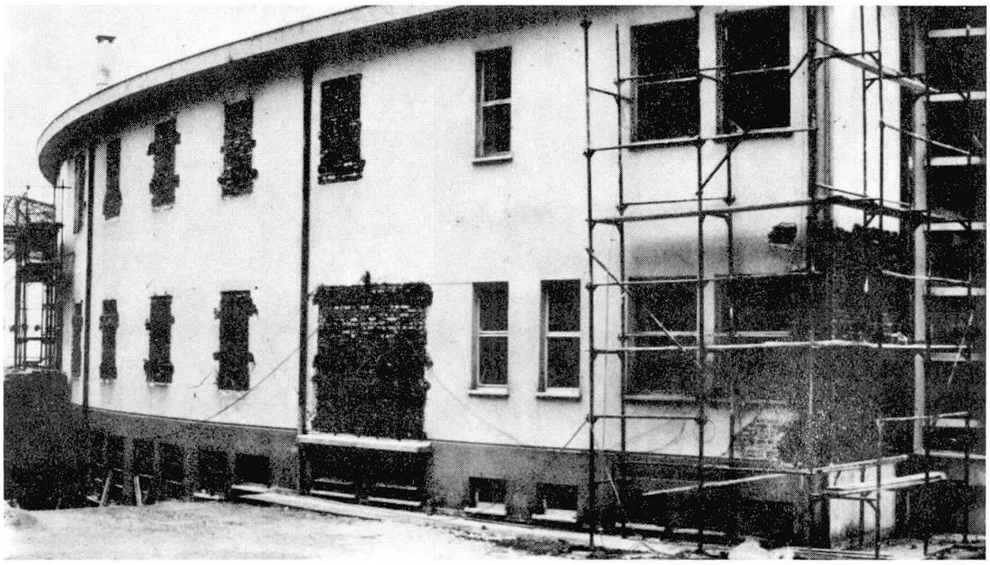


Figure 10: (after September 15th): Business building SBUELZ in Tricesimo. To strengthen the carrying capacity, the door and window openings were walled in. The vibration behaviour of the building was so improved that, during renewed earthquake stress hardly any further damage occured as opposed to the destruction which occured during the earthquake of May 6th.

A lessening of the earthquake load is to be expected, above all, by the reduction in weight of the non-supporting building elements. The reduction in weight of secondary building elements and installations has the effect of reducing almost proportionately the strain on the supporting structure and, therefore, increasing the carrying capacity during renewed earthquake stress. In an industrial building (Figures 11 and 12), for example, the heavy reinforced concrete façade slabs were replaced by walls of lighter steel. Not only the strengthening of the columns but also the lessening of the earthquake load contributed considerably to the fact that the building remained undamaged during the September shocks.

It is obvious that the civil engineer must incorporate earthquake load in the calculation and construction of buildings to be newly erected and in the repair of damaged structures. As demonstrated by the positive behaviour of the newer buildings in the area of Tolmezzo, designed in accordance with the now valid Italian earthquake code, which offer sufficient safety for the life of the occupants. At the same time, however, it should be noted that it is accepted that building damage will occur and the protection of the inhabitants is guaranteed during a limited number of strong earthquakes only. If it is required that a building (for example hospitals, utilities) will be able to continue functioning after an earthquake, then the normal earthquake building code is insufficient. A dynamic analysis of the building behaviour should be made and the structures should be designed in accordance with the loads actually occuring during an earthquake. An earthquake risk study can serve as a basis for the selection of the appropriate earthquake input parameters.

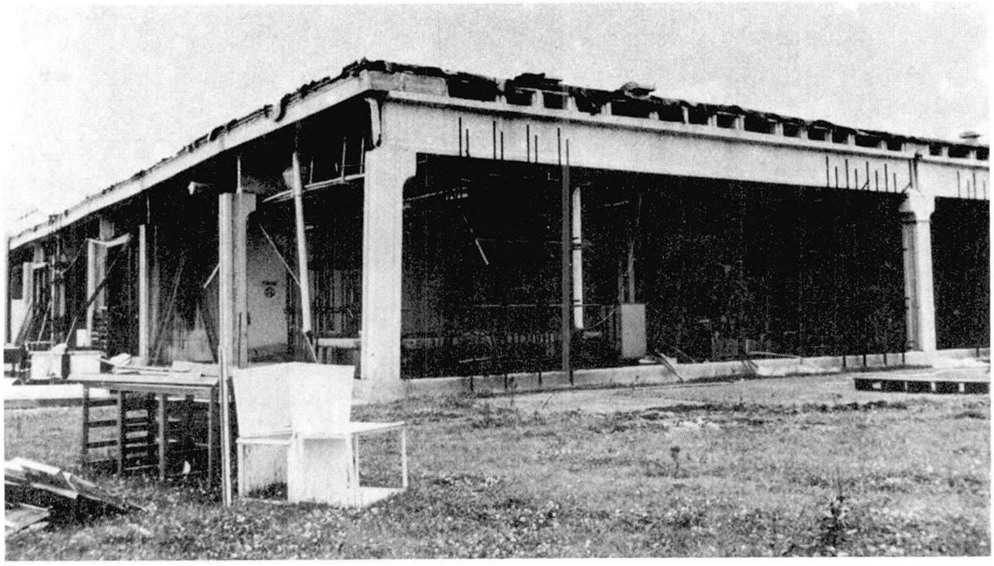


Figure 11: (after May 6th): Factory building near Artegna. Severe displacement of the prefabricated reinforced concrete framework together with distortion of the foundation and tilting of a corner column. A large number of the only lightly secured reinforced concrete façade elements were thrown off.

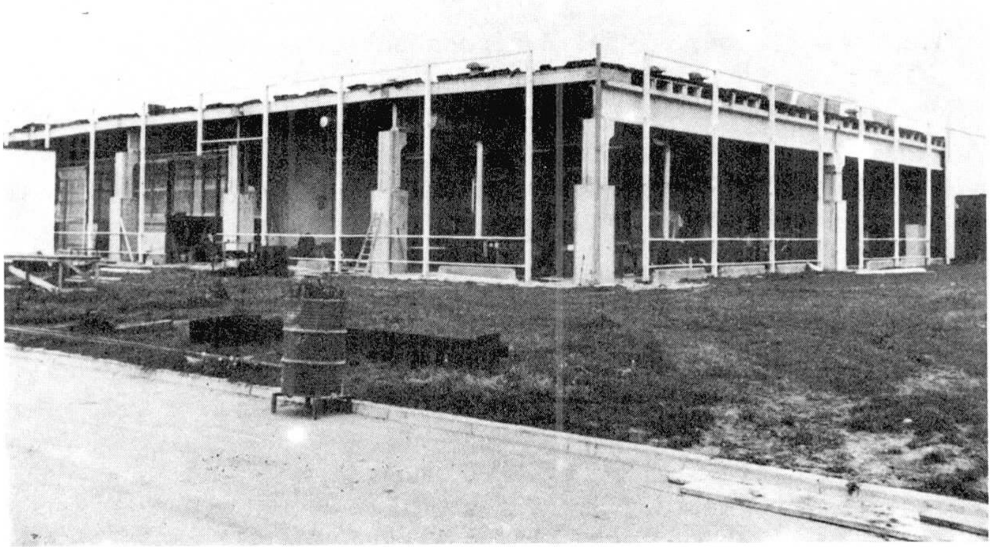


Figure 12: (after September 15th): Factory building near Artegna, after repair, without further earthquake damage. In order to increase the carrying capacity, the concrete columns were surrounded with a 15 cm strong concrete sheath. The earthquake load was reduced by replacing the heavy concrete façade elements by a light metal façade.

3. A FEW GENERAL REMARKS ON EARTHQUAKE BEHAVIOUR OF BUILDINGS

A closer examination of the effects of the earthquake on various types of structures reveals that much of the damage originates from just a few basic structural defects. We have tried to derive several ground rules for the design of structures. Although these conclusions can also largely be confirmed by observation of other earthquakes, the damage described here is peculiar to this particular earthquake and epicentral region.

The main cause of the extensive damage is certainly the fact that the effects of an earthquake did not have to and therefore were not taken into considerations in the design of the buildings. If engineers had only visualized that their structures would have to undergo the displacement, velocity and acceleration of earthquakes, the few selfevident consequences in the layout of the structures would have avoided most of the damage even without a proper earthquake design.

3.1. Structural Elements

3.1.1. Walls

Walls and partitions consisting of brick and masonry are both rigid and brittle. Where the walls are insufficiently strong or where many openings exist, the masonry walls are no longer able to absorb horizontal forces. When overstrained, these walls crack mostly crosswise under 45° (Figure 13), the crack spreading, either along the mortar joints or in the bricks. Because of the brittle nature of masonry constructions, the cracks widen, joints gape open or the walls concerned even collapse. In a skeleton construction, the reinforced concrete framework can in certain cases continue to uphold the weight of the buildings. For purely masonry construction, on the other hand, at least a partial collapse of the building is unavoidable.

Figure 13: Dwelling house with workshop near Artegna. Basement in reinforced concrete and the upper stories in masoning without framing. Typical diagonal cross cracks in a wall of the ground floor.

3.1.2 Reinforced Concrete Columns

Since reinforced concrete columns are, in general, considerably more flexible than walls, the latter carry partically the entire earthquake force. However, in open constructions the entire stress is carried by the columns. The free-standing reinforced concrete columns of one-storey storage sheds were mostly strong enough to absorb the stress without being destroyed, in many cases even without incurring lasting cracks. By partial stiffening, for instance by means of an annex or installations or heavy rigid upper floors, higher stress results, which usually leads to plastic deformation at both ends of the columns. Hence, the reinforcement, overstressed by tension, can buckle as a result of the alternating action (Figure 14). The related cracking of the concrete and the buckling cannot be significantly reduced even by means of closely spaced stirrups.

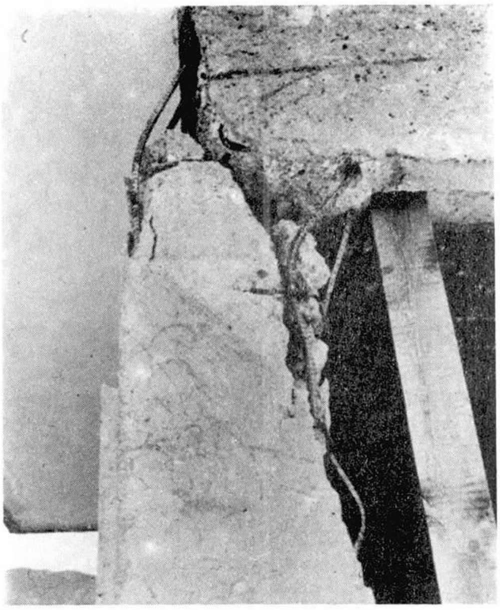


Figure 14: Shearing-off of a column at its connection with the crossbrain due to insufficient stirrups.

The ability of the resulting plastic joint to rotate is, however, increased and a sheer failure prevented.

In the event that it is impossible to design the columns, taking actual earthquake forces into consideration, then at least the plastic deformation of the columns in all directions must be guaranteed. The movements should not be hindered by any secondary elements. An improved building method for the prevention of collapse could, therefore, be to shape the columns in a manner that the plastic hinges, necessary to absorb energy, are formed in the crossbeams.

3.2. Structural Systems

3.2.1. Open Ground Floors

Open or only slightly stiffened ground floors, mostly for commercial use, are particularly vulnerable. The locally severe destruction in the area of such weak spots caused the collapse of entire buildings or made their demolition necessary, even with otherwise only minor damage, because restoration would have been too difficult (Figure 15).

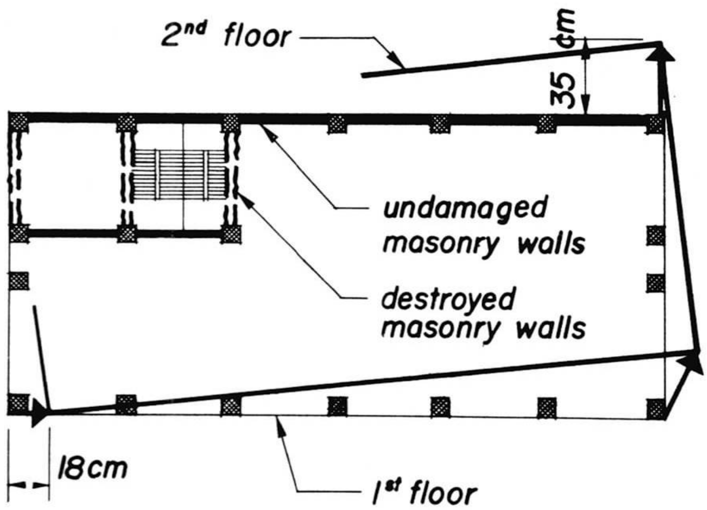
Greatly differing conditions of rigidity in a supporting structure result in local weak spots which are the first to be overstrained in an earthquake and plastically deformed. Hence the stronger parts of the building are no longer irreversibly deformed and energy absorption is limited to the weaker building parts. Consequently, an evenly distributed plastification of the entire structure is necessary to ensure that destruction remains within acceptable limits.

3.2.2. Torsional Action

From the point of view of the structural system, many symmetrical structures suffered damage due to the additional twisting motion of the building around its vertical axis. As a result of the superimposed movement, some parts of the building are relieved whilst others are considerably more deformed than they would be due to translational movements only. Torsional loads are caused by the unsymmetrical layout of the structural system, but also by contingencies arising in the rigidity and execution of partitioning walls and additional fittings (Figure 15). The consequences of torsional strain can only be met by appropriate consideration in the design including provision for sufficient torsional rigidity of the building. Due to the incalculable influence of secondary elements, which are not designed to carry vertical loads, an asymmetry in the ground plan can hardly be excluded.

Figure 15:

Three-storey dwelling house with shop in the ground floor near Artegna. Reinforced concrete frame with brick partitioning walls in the upper floors and mostly open ground floor. Plastic hinges at bottom and top of the ground floor reinforced concrete columns caused large deformations. No damage in the upper floors.



The ground plan of the dwelling house with the open ground floor shown before. Twisting of the building around the staircase stiffened with masonry walls.

3.2.3. Attached Buildings

Severe damage could be located in structures composed of building sections with greatly differing rigidity due to diverse types of construction (for instance, reinforced concrete frame and pure brick) or which varied considerably in their design (Figure 16). This damage occured because the individual deformation of each component was obstructed.

This problem can be overcome by arranging the joints as to divide the structure into sections, each with its own clearly distinct vibration behaviour. The joints should be made adequately wide since numerous uncertainties make an exact calculation impossible. It must be taken into consideration that, for example, the deformation usually provided for in a homogenous supporting structure can turn out to be considerably larger due to the formation of cracks or plastification. An adequate freedom of movement, therefore, allows for greater plastification and a larger capacity to carry earthquake stress.

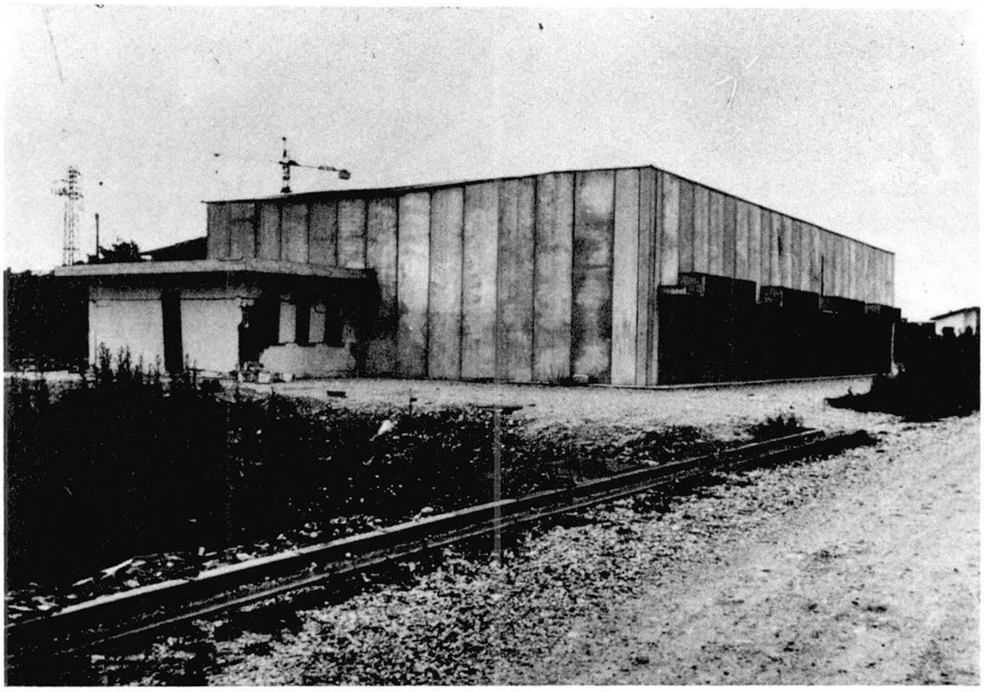


Figure 16: Prefabricated storage shed with brick annex in Gemona. Side wall panels slightly caved in by impact with rigid annex. Upper part of the annex shorn off and pushed over by the impact force due to insufficiently wide joints.

3.2.4. Special Structures

Special structures (e.g., bridges and water-towers) (Figure 17), because of their unusual form and distribution of mass, necessitate a dynamic analysis which takes the vibration behaviour of the structure and the real properties of an anticipated earthquake into consideration.

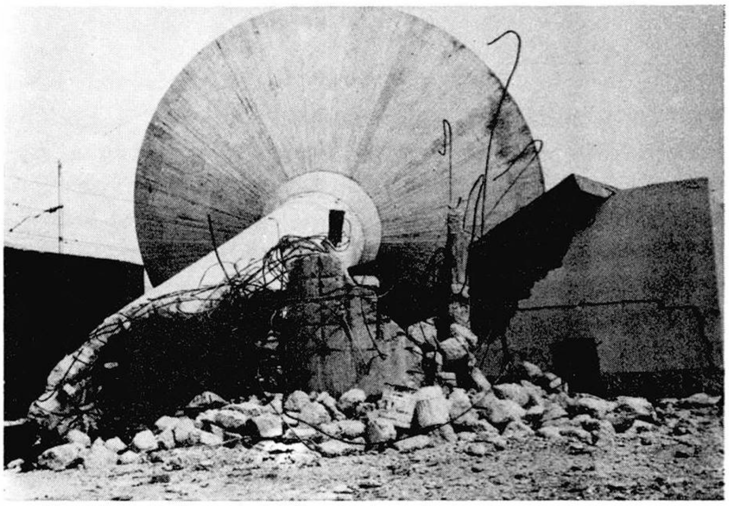


Figure 17: Overturned water tower belonging to the Italian State Railways in Gemona station. Foot of the shaft completely destroyed and concrete shattered.

3.2.5. Secondary Structural Elements

All the components and fixtures, in particular dividing walls, attached façade slabs, covering, pipes and other fittings, which form part of a structure, influence the response of the supporting structure (Figure 18). These secondary structural elements are generally not included in the analysis of the supporting structure and, therefore, not designed against earthquake forces. They can, even when subjected to only slight movements, suffer damage which produces an increasing alteration in the vibration behaviour. It cannot be predicted whether this influence will prove to be positive due to greater absorption of energy or negative due, for example, to added torsional motion. As far as possible, in order to ensure that secondary elements survive earthquake loads without substantial damage, they should be analysed and designed together with the supporting system.

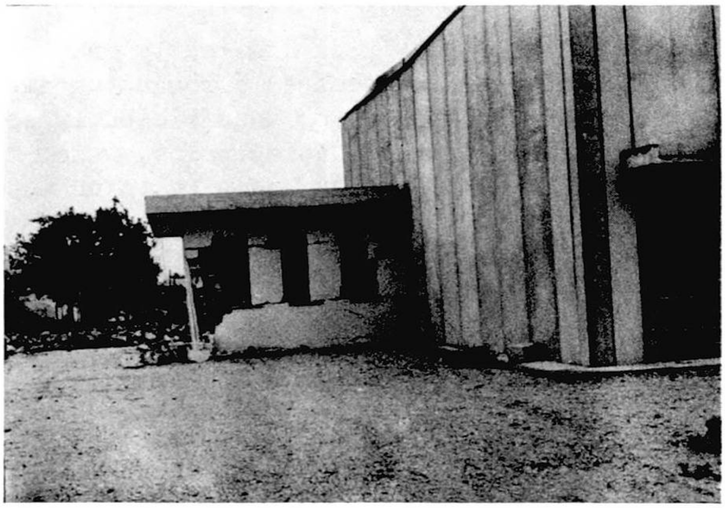


Figure 18: Prefabricated storage shed in Gemona as shown before. The supporting frames and the wall panels generally not damaged because of energy absorption in the material of the joints between the single panels.

3.3. Joints and Supports

3.3.1. Joining of Structural Elements

If prefabricated structures are designed only in accordance with the Standards laid down for earthquake forces or these forces are overlooked altoghether, then the result is greatly underdimensioned connections of the structure elements Load bearing connexions should be properly designed against the expected dynamic forces. Purely friction-type joints are no longer sufficient to transfer the forces that arise, even from only weak earthquake loads (Figure 19).

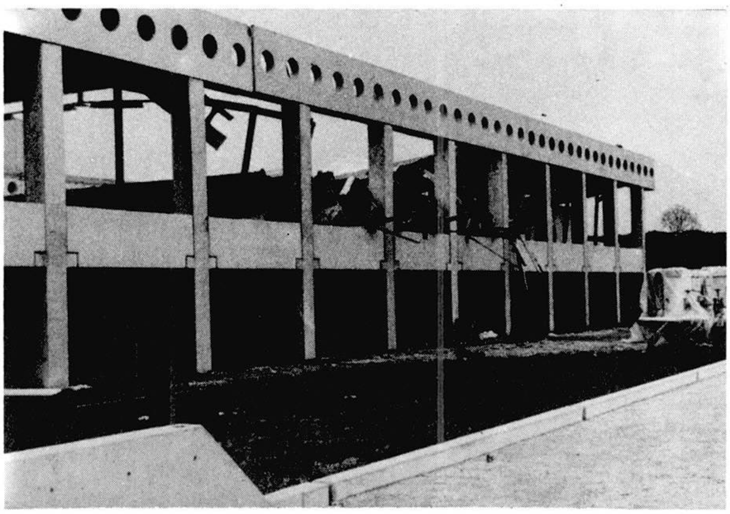


Figure 19: Heavily damaged prefabricated factory shed near Osoppo with roof girders fallen down. Friction joints insufficient to provide structural stability.

3.3.2. Fixation of Secondary Structural Elements

Building parts (such as prefabricated façade slabs and dividing walls and fittings, particularly machines, storage racks and pipes), which are not part of the supporting structure, are usually either directly or indirectly connected to it. Due to the action of the earthquake, much damage occured through the displacement or collapse of façade slabs which were unconnected or insufficiently secured (Figure 20). The actual displacement occuring at the fixation point, which can be considerably larger than the one of the ground shock, must be taken into consideration in the fixation of secondary elements.

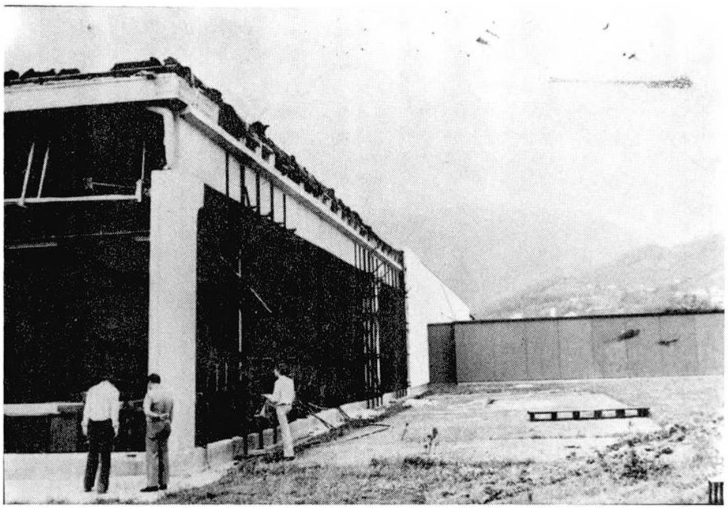


Figure 20: Prefabricated factory shed near Artegna. Wall panels fallen out during the earthquake because of insufficient fixation.

4. MERIT AND LIMITS OF EARTHQUAKE DESIGN SPECIFICATIONS

The region at the southern foot of the Alps hit by the May 6th earthquake has been known for centuries as an earthquake area. However, in the major part of the epicentral area, no laws existed for the design of structures. Such laws applied only for new buildings in a small part of the area.

The Italian State Administration has enacted special regulations for earthquake-prone areas and has repeatedly brought them up-to-date. Using the Code, design earthquake loads are determined by statical or dynamic analysis. An average horizontal acceleration will result, which is about 7 percent of the gravity acceleration g. Comparision of horizontal design accelerations given by the Code with those produced by an earthquake with the Intensity IX (Figure 21) shows large discrepancies.

The Code values are significantly smaller because it is assumed that strong energy absorption will occur due to inelastic behaviour of materials and elements. But this means that the structure must be capable of absorbing the appropriate energy. Consequently, plastic deformation and therefore damage or maybe even collapse can result.

On present day standards, this is not good enough. Originally, Codes were drawn up merely to prevent the collapse of a structure and thus save lives. Today, our more highly developed society demands that at least life-lines (i.e., hospitals, water supplies, electricity, etc.) continue to function after an earthquake. As a result, it is imperative that a Code be introduced incorporating design specifications which distinguish between the various functions for which structures are built.

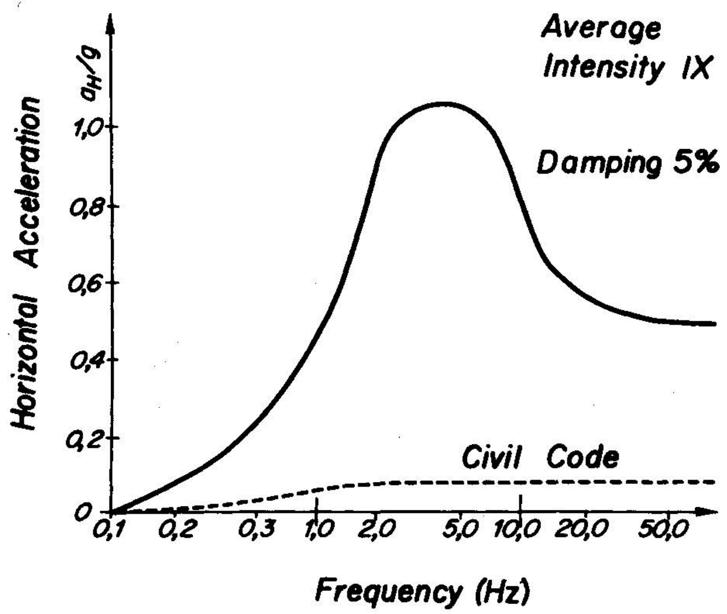


Figure 21: Horizontal ground acceleration for earthquakes of intensity IX (MSK) (U.S. Atomic Energy Commission, WASH 1255). The dashed line gives the disign ground acceleration according to the conventional aseimic building code.

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