OLD CITY OF DUBROVNIK, No 95

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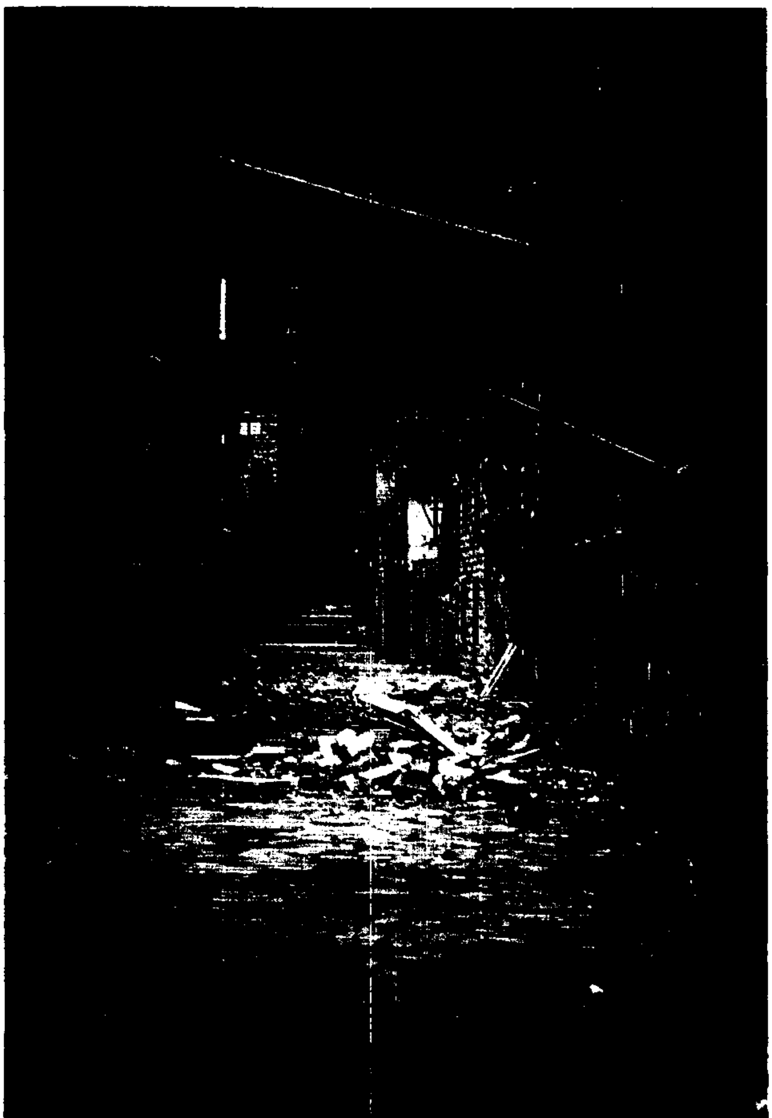

Mission to Dubrovnik and Ston

Earthquake 5th September 1996

TECHNICAL REPORT

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Collaborator:
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Rome, 26th November 1996

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Chair of Structural Restoration of
Monuments and Historic Buildings

Prof. Ing. Giorgio Croci

UNESCO

WORLD HERITAGE CENTRE

Mission to Dubrovnik and Ston after the earthquake of September 1996

Technical Report

1. INTRODUCTION

1.1. The object of the mission

The region of Dubrovnik was struck by a strong earthquake the 5th of September 1996.

In November 12th, 13th, 14th, and 15th, the area was visited by Prof. Eng. Giorgio Croci and his collaborator Eng. Alessandro Bonci.

The object of the mission was to survey the effects of the earthquake and the entity of damage, to indicate the urgency of the actions to be taken and to suggest the criteria for the structural restoration.

1.2. The characteristics of the earthquake

The data about the characteristics of the earthquake are now being elaborated by local experts; the following data are therefore preliminary information given by Mr. Vlado Kuk, from "Geofizicki Institut" of Zagreb.

The first shake of the earthquake occurred at 10.45 p.m. of September the 5th, with epicentre in the Bay of Janska, about 2 km far from the coast (fig. 1, 2), and about 30 km NW from Dubrovnik; it lasted about 5 seconds, with a peak ground acceleration of about 0.6 g and an intensity of about 6 degrees of Richter scale.

In Ston (fig. 3, 4, 5) and some nearby villages the earthquake is considered to have produced effects of VIII degree of Mercalli scale, reaching exceptionally IX degree.

Other shocks were recorded on September 17th and September 19th, with an intensity of, respectively, 5.5 and 5.4 degrees of Richter scale.

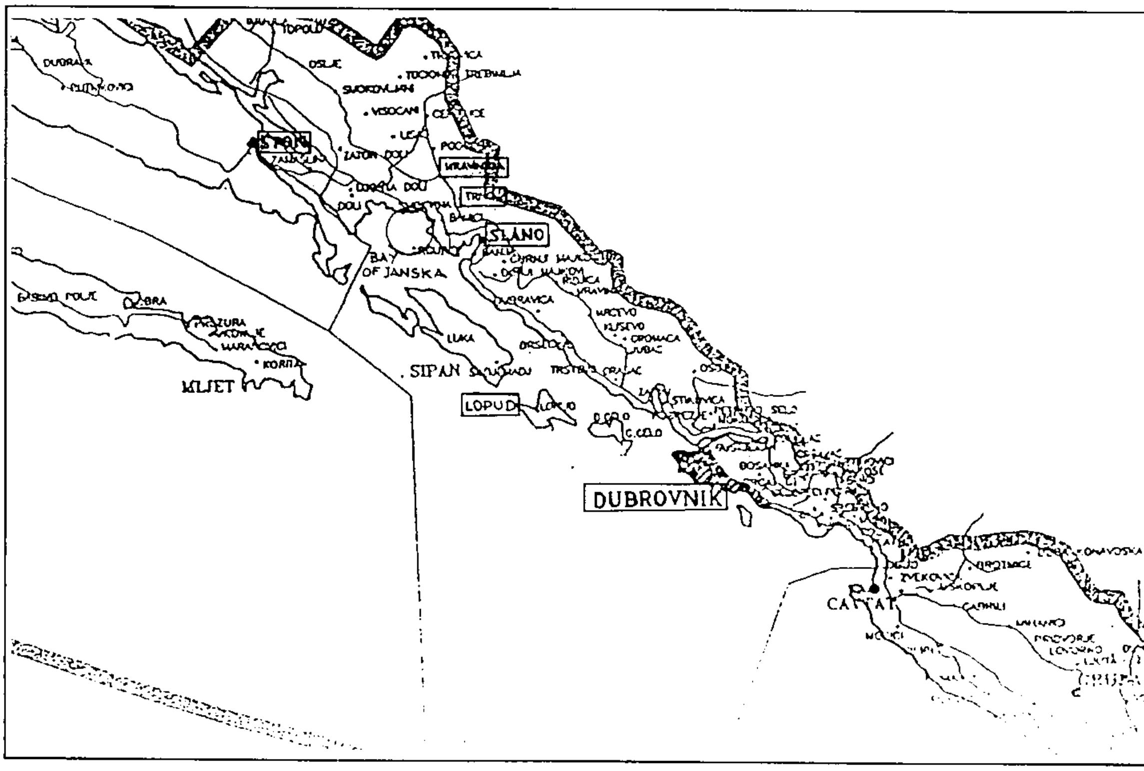


Fig. 1 The region of the earthquake

Fig. 2 The Bay of Janska, epicentre of the earthquake

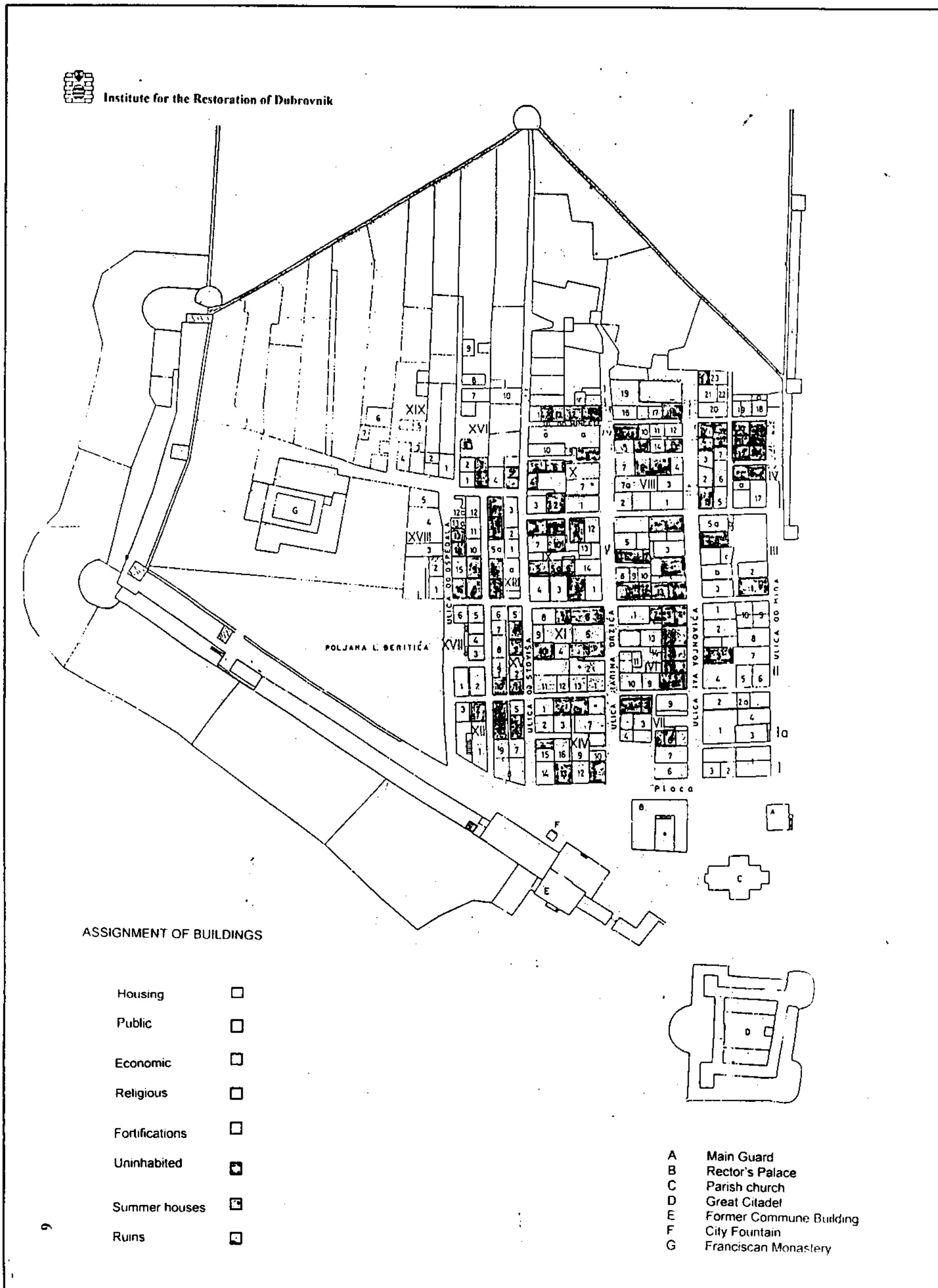


Fig. 3 The map of Ston (from "Institut for the Restoration of Dubrovnik"

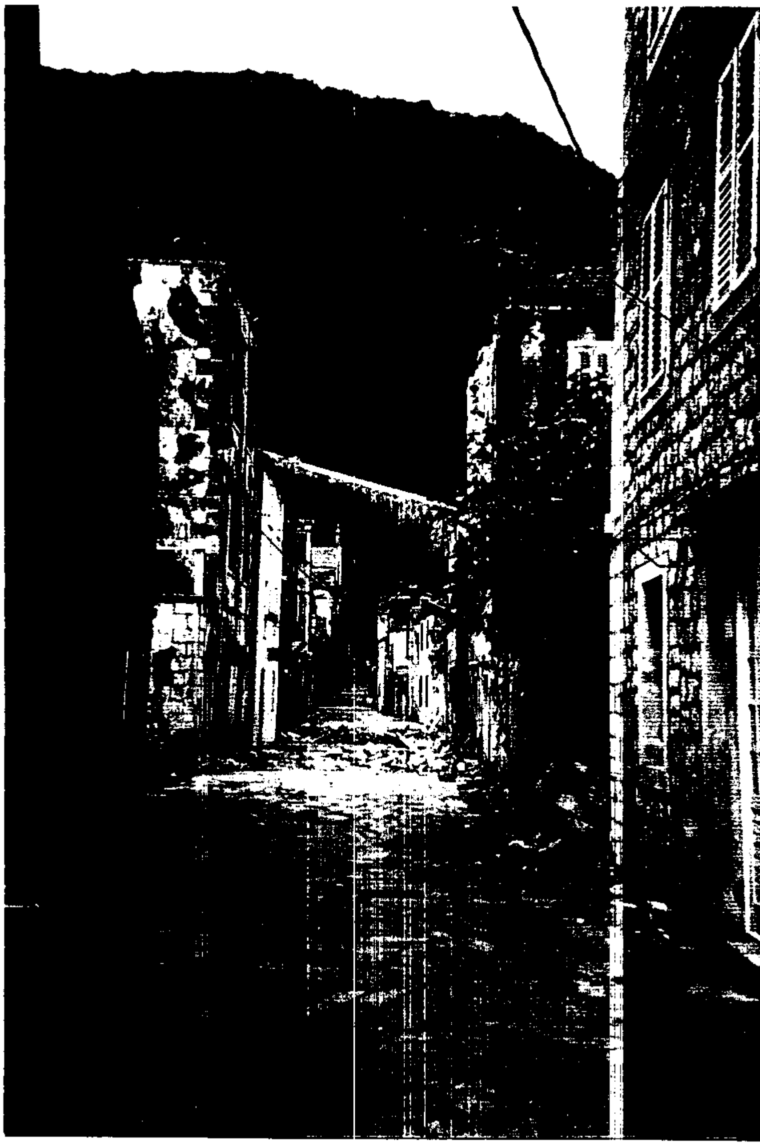


Fig. 4 Ston

Fig. 5 Ston

1.3. The damage

According with the data of the "Institute for the Restoration of Dubrovnik", about 1400 buildings were damaged by the earthquake of September, and 474 of these were retained uninhabitable.

During the mission the following localities were visited.

<u>Ston</u>

This historical small town (fig. 3, 4, 5) lays about 10 km NW from the epicentre of the earthquake, and it is the city where the earthquake produced the largest part of collapses and damage.

The 250 buildings (including in this number public buildings, churches, ...) inside the city walls were all damaged, and 100 of them collapsed or were so seriously damaged that the inhabitants were obliged to leave them.

In the zone of the municipality of Ston 127 buildings were considered uninhabitable

<u>Mali Ston</u>

In Mali Ston (the Little Stone) the buildings do not show significant damage; only the castle suffered a limited collapse and some cracks were produced (fig. 6).

<u>Trnova</u>

The masonry buildings of the little village of Trnova (Fig. 7), very close to the epicentre of the earthquake, were all seriously damaged, and most of them collapsed.

<u>Mavrinca</u>

In the little village of Mavrinca many houses were damaged or collapsed; the roof of the church, not connected to the wall, slipped away (form 26).

<u>Slano</u>

The dock suffered relevant cracks.

<u>Isle of Lopud</u>

Not relevant damage were produced in the Isle of Lopud (fig. 8); in the Benedictine Church some ancient wood cornices fell down from the wall (form 23).

<u>Dubrovnik</u>

The earthquake of September 1996 didn't produce relevant damage in Dubrovnik: only some old cracks, dating back to the earthquake of 1979 (fig. 9), increased.

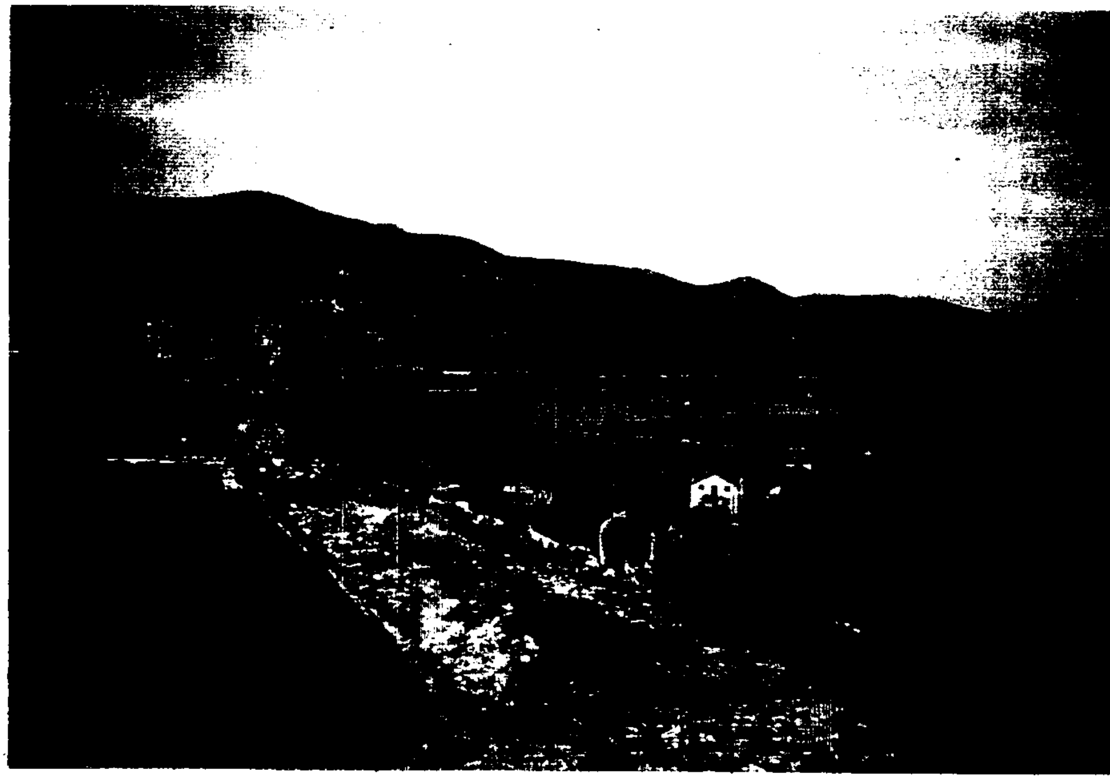


Fig. 6 The Castle of Mali Ston (The Little Ston)

Fig. 7 The village of Trnova

Fig. 8 The Isle of Lopud

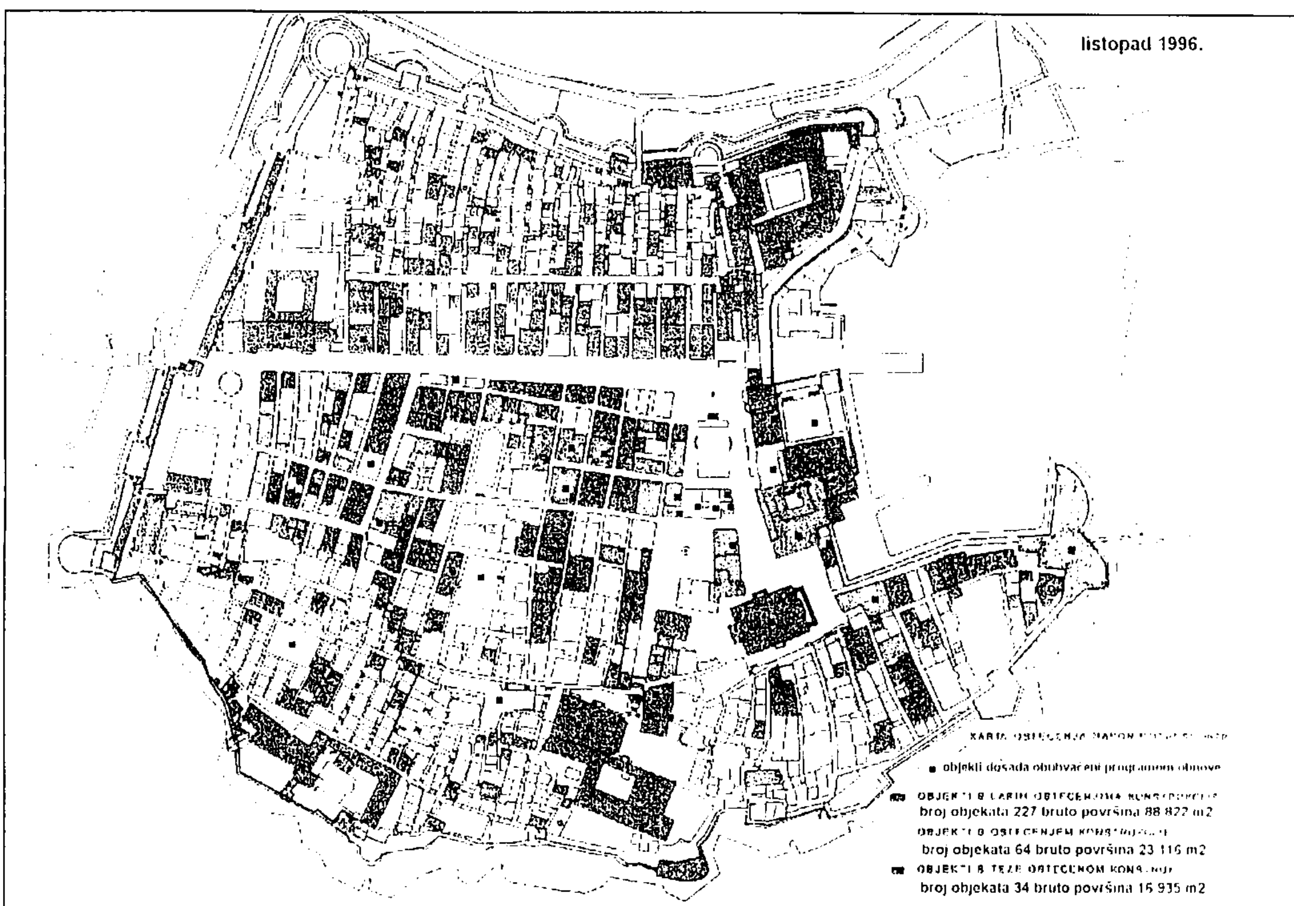


Fig. 9 Map of Dubrovnik with the damage produced by the earthquake of 1979 (from "Institute for the Restoration of Dubrovnik")

2. BUILDING TYPOLOGY IN THE AREA

2.1. The characteristics of the historic building

Several buildings date back to 14th, 15th, and 16th century.

Apart from some cases (the Castle of Mali Ston -fig. 6-, the churches of Mavrinca and Ston -forms 26 and 15-), most part of the buildings affected by the earthquake is represented by houses with one, two or three storeys and a very simple structural conception.

The main walls are sac masonry (generally about 60 cm thickness) with the faces made of limestone blocks. The external facing stones of the sack masonry are often not sufficiently linked to the back masonry, being the latter of poor quality (see form 32).

Floors and roofs are made of timber; often they are supported by little stone cantilevers inserted in the wall masonry; over these cantilevers lays a timber beam parallel to the wall which supports the floor (fig. 10, 11).

This system offers the following pros and cons:

- it does not create weak zones, as it often happens when the timber beams are directly inserted in the walls
- it avoids the risk the heads of the beams to be deteriorated by the water rain, which easily reach the head of the beam when it is inserted in the walls
- the construction can proceed faster and better organised
- the bending moment transmitted by the floors to the walls is well defined and independent by the relative stiffnesses.

On the other hand this system, when not improved with supplementary chains, provides a very weak connection, especially as regard seismic actions.

In the towns of Ston and Dubrovnik, realised with the same urbanistic structure, the houses are not isolated, but part of blocks (fig. 3, 9). This arrangement can produce supplementary twisting effects depending on the shape of the block.

Finally, it must be noticed that the houses of little villages as Mravinca and Trnova, are often realised with poor materials and rudimentary techniques, and this surely contributed to the ruinous effects of the earthquake.

2.2. The typical structural behaviour of the buildings laying in the area

The structural behaviour under the effect of the seismic actions can be synthesised as follows.

The component of the seismic action *perpendicular* to the wall involves on the one hand the stability of the wall itself and on the other the detachment of the wall by the other which it is connected to.

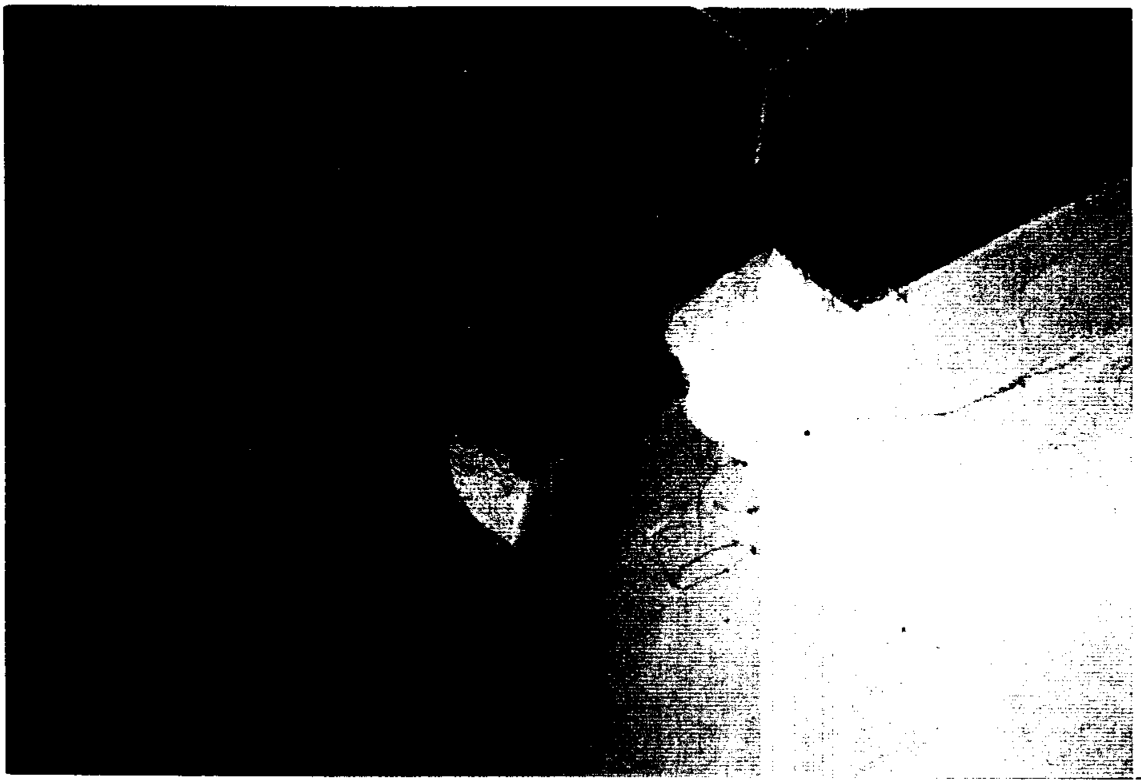


Fig. 10 The system for the support of the roof

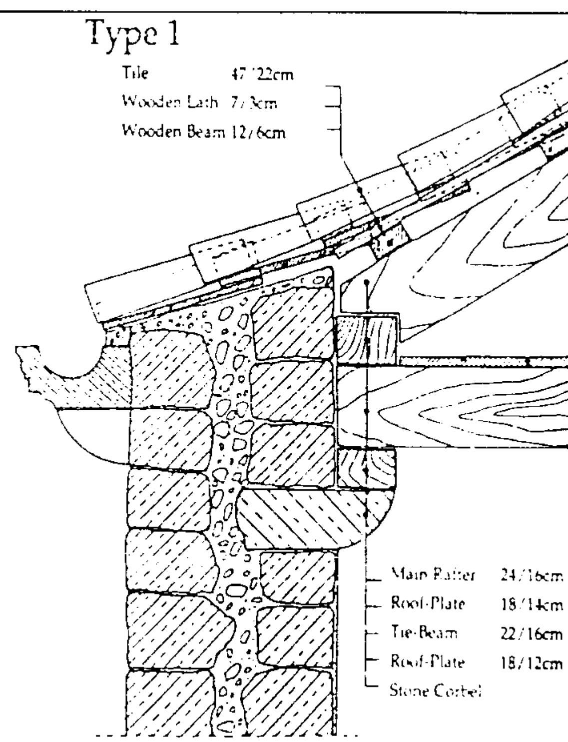


Fig. 11 Scheme of the system for the support of the roof

As regard its intrinsic stability it is necessary to develop an "arch effect" (fig. 12) and therefore to have appropriate restraints at the boundaries.

The component of the seismic action parallel to the wall usually produces effect smaller than those produced in the situation described above; depending mainly on the geometry of the wall two basic kinds of behaviour can develop: a "shear type behaviour" (the more resistant and less frequent one, fig. 13a) or a "flexural behaviour" (the weaker and more frequent one, fig 13b).

The main characteristics of damage and collapses can be synthesised as follows:

- detachment of a portion of the wall subjected to seismic action perpendicular to its plane and in particular of the bands between the roof and the windows (fig. 14)
- global detachment of the wall (fig. 15)
- cross cracks in the wall (fig. 16); they basically follow the general schemes of fig. 13
- detachment of the corners due to the combined action of the seismic forces parallel and perpendicular to the façades (fig 17)

The bearing capacity associated with these structural behaviours is as higher as better are fulfilled the following conditions:

- cohesion of the material
- connection of the roof to the walls provided that any thrust is prevented
- connection of the floors to the walls
- connection between the walls

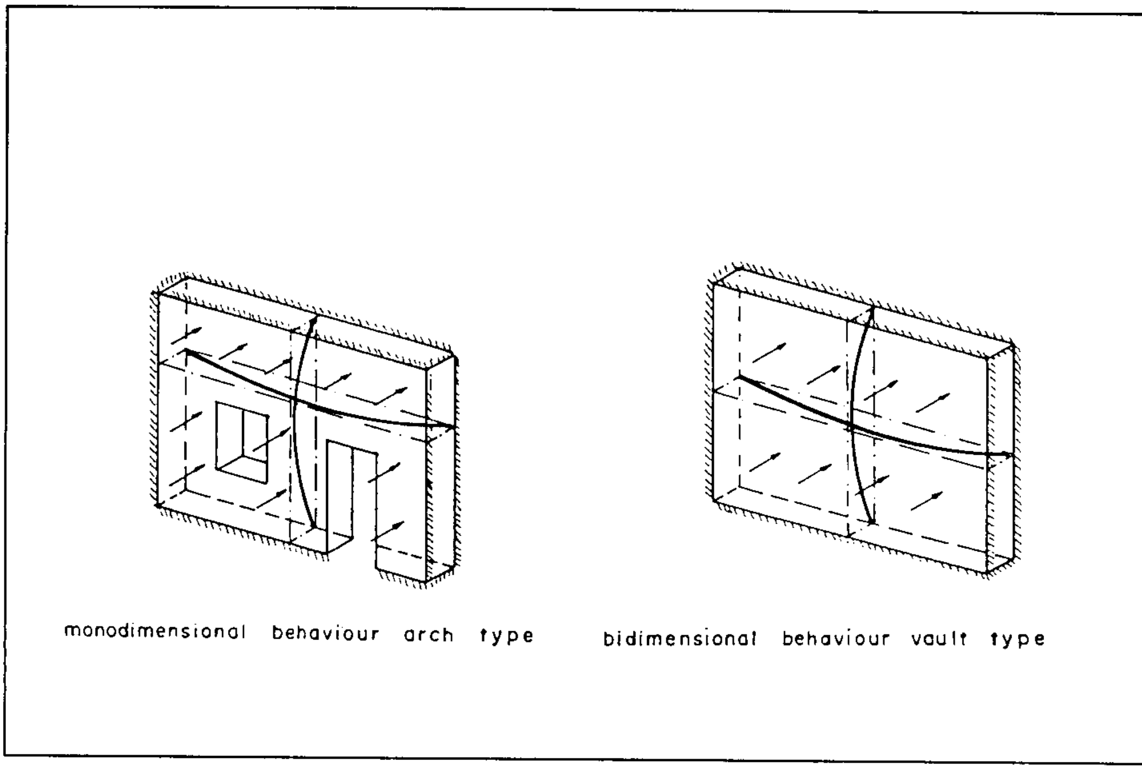


Fig. 12 Scheme of the development of the "arch effect"

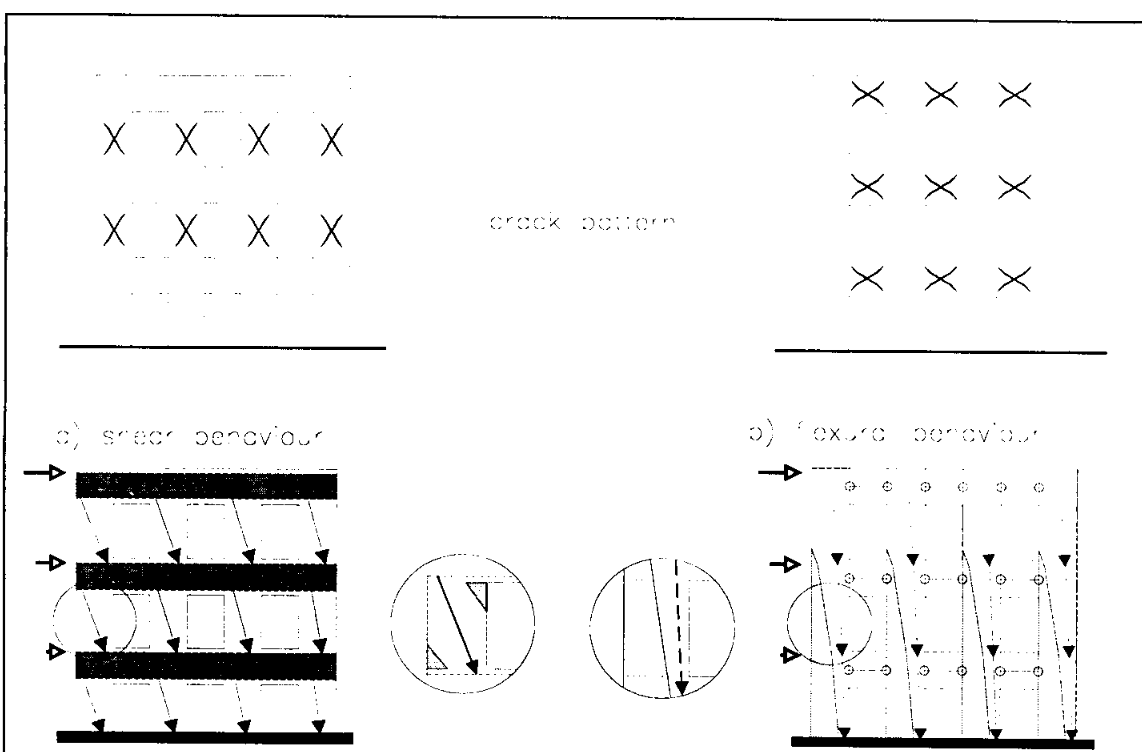


Fig. 13 Typical crack patterns and structural behaviours of walls parallel to the seismic action

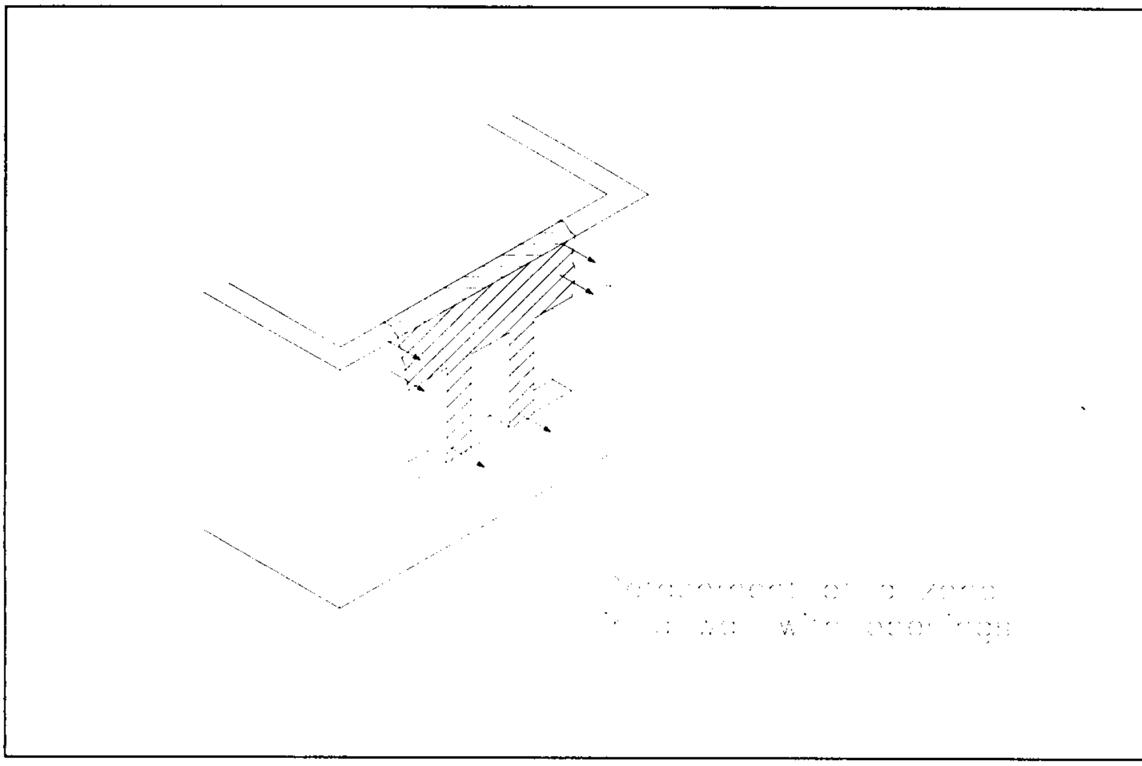


Fig. 14 Possible shear collapse of the zone under the roof

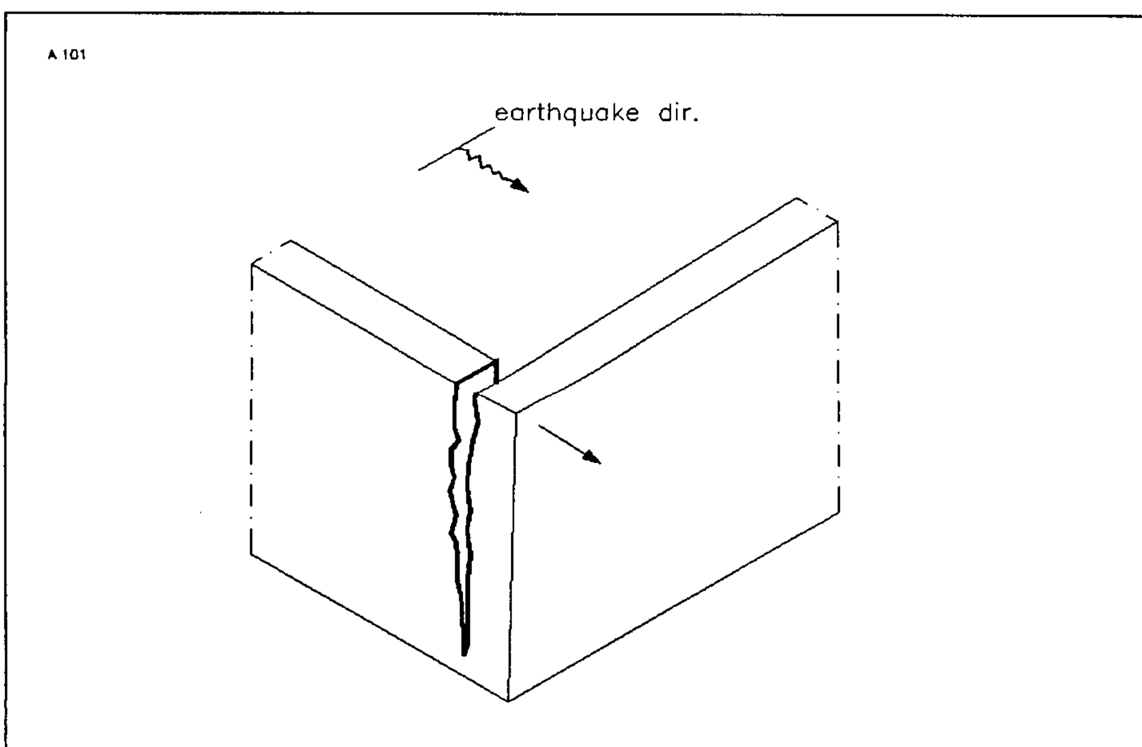


Fig. 15 Detachment of perpendicular walls

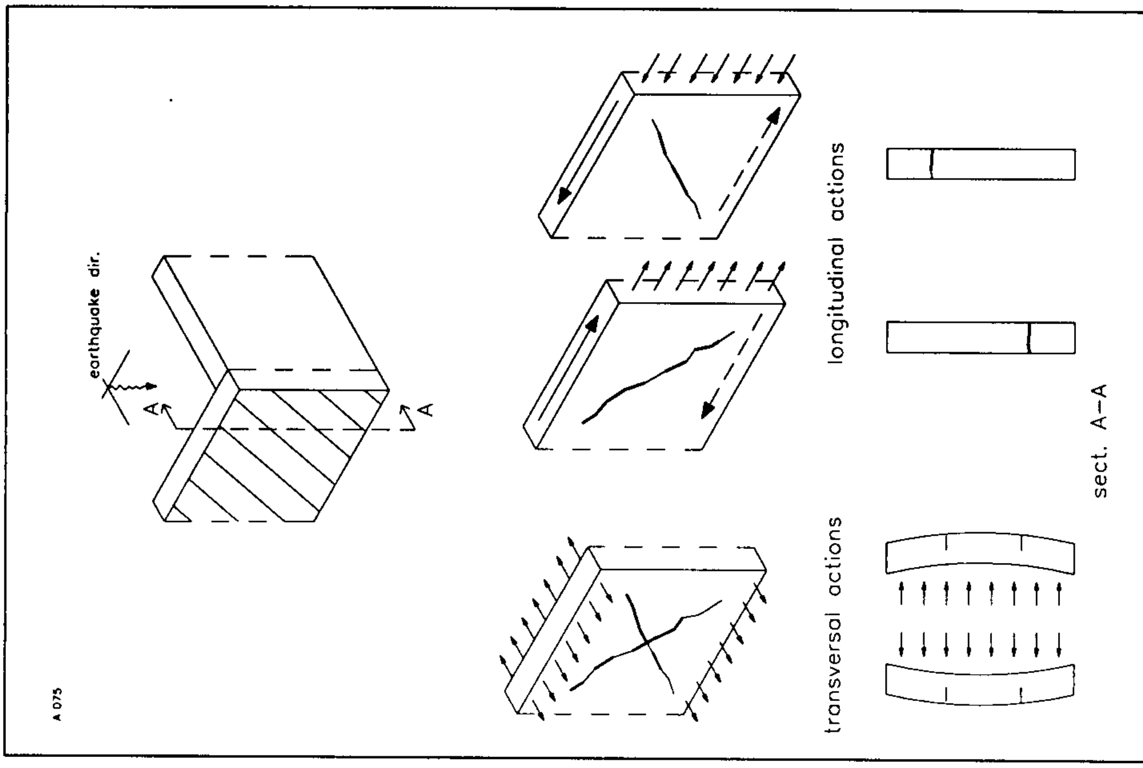


Fig. 16 Cross cracks in the walls

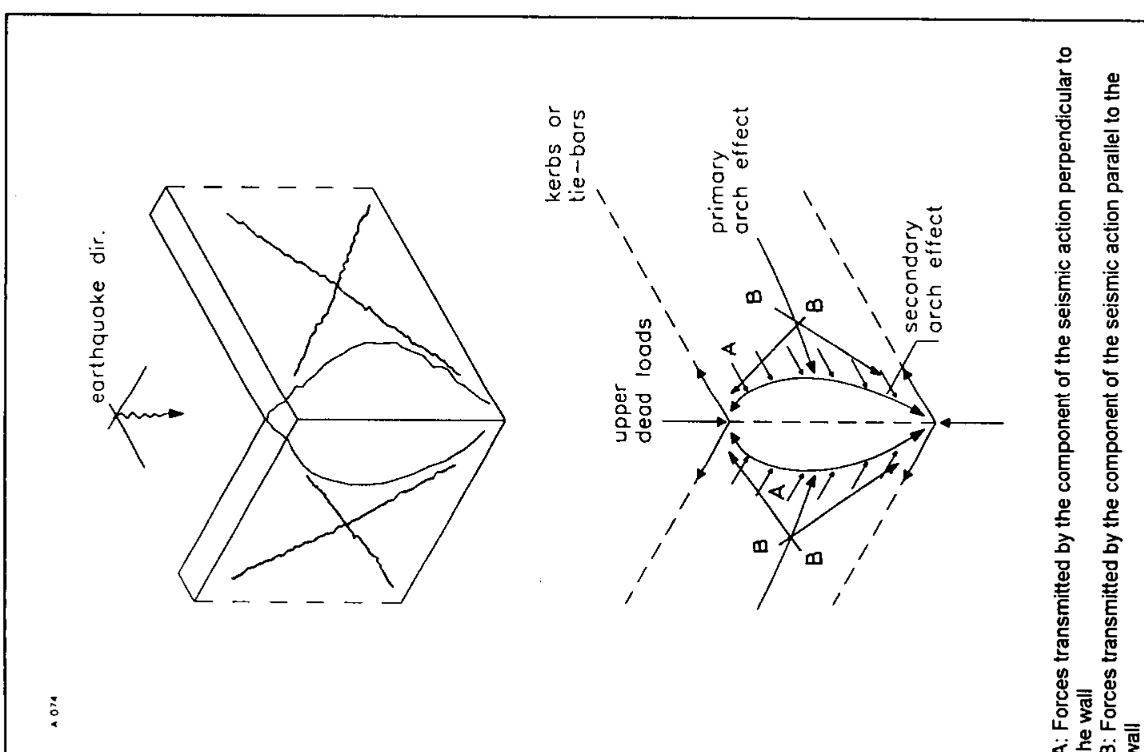


Fig. 17 Detachment of the corner

3. DAMAGE AND COLLAPSES

Detailed analysis of the different kind of damage will be discussed below, having organised in different forms the material acquired during the survey.

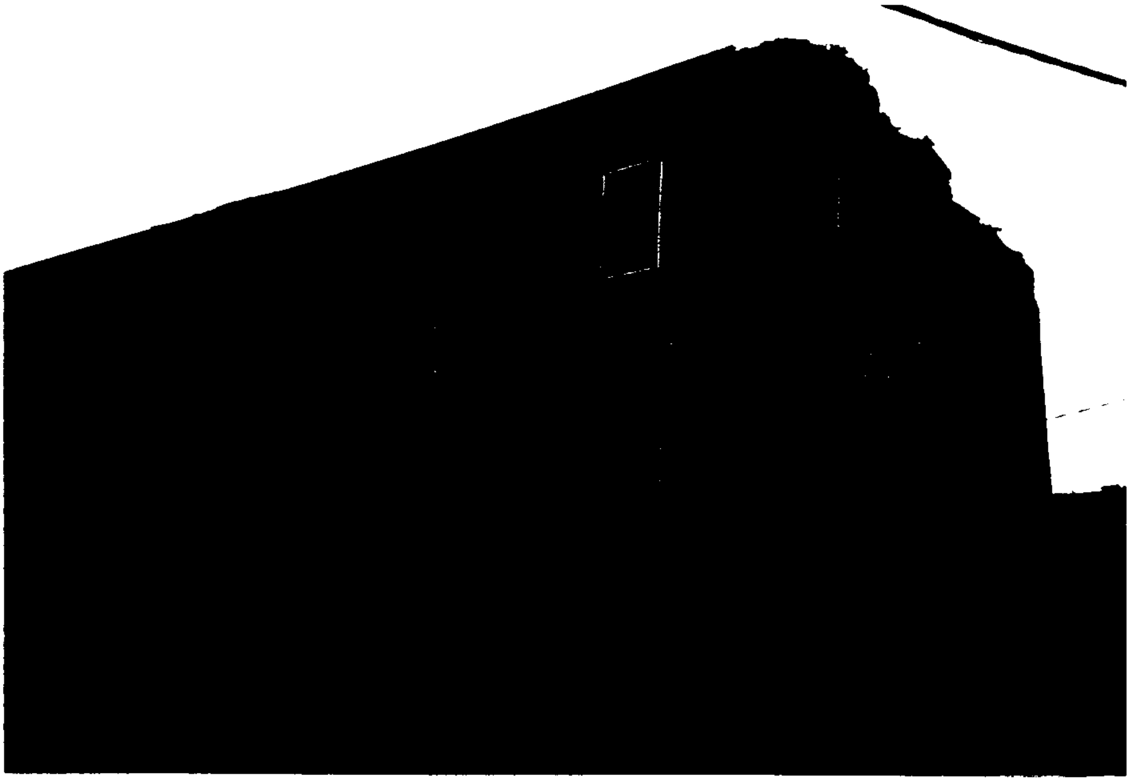
Forms from n° 1 to n° 22 show buildings having a relevant historical value and whose performance under the seismic actions appeared to be representative of the buildings typologies. Each form contains 3 topics: the causes of damage or collapse, the measure that could have been taken to prevent or reduce the damage and, finally, the possible remedial actions in the present situation; these actions in many cases are urgent to prevent further deterioration and increased damage.

In § 4 these remedial actions will then be summarised.

Forms from 23 to 32 finally show and discuss particular types of damage frequently surveyed and therefore representative of the actual situation.

Form n°

1



Ston
Building 2, block Ia
North façade

The causes of the damage or collapse

The North façade is almost parallel to the seismic action; typical damage produced by forces acting in the plane of the wall are visible:

1. Cracks in the zone under and over the windows, producing an independent cantilever flexural behaviour (fig. 13b); detail in form n° 2
2. Inclined cracks at the corner (fig. 16)
3. Detachment of the perpendicular wall (fig. 15); detail in form n° 3
4. Slippage of the window posts; detail in form n° 2

Preventive measures that could have reduced the damage

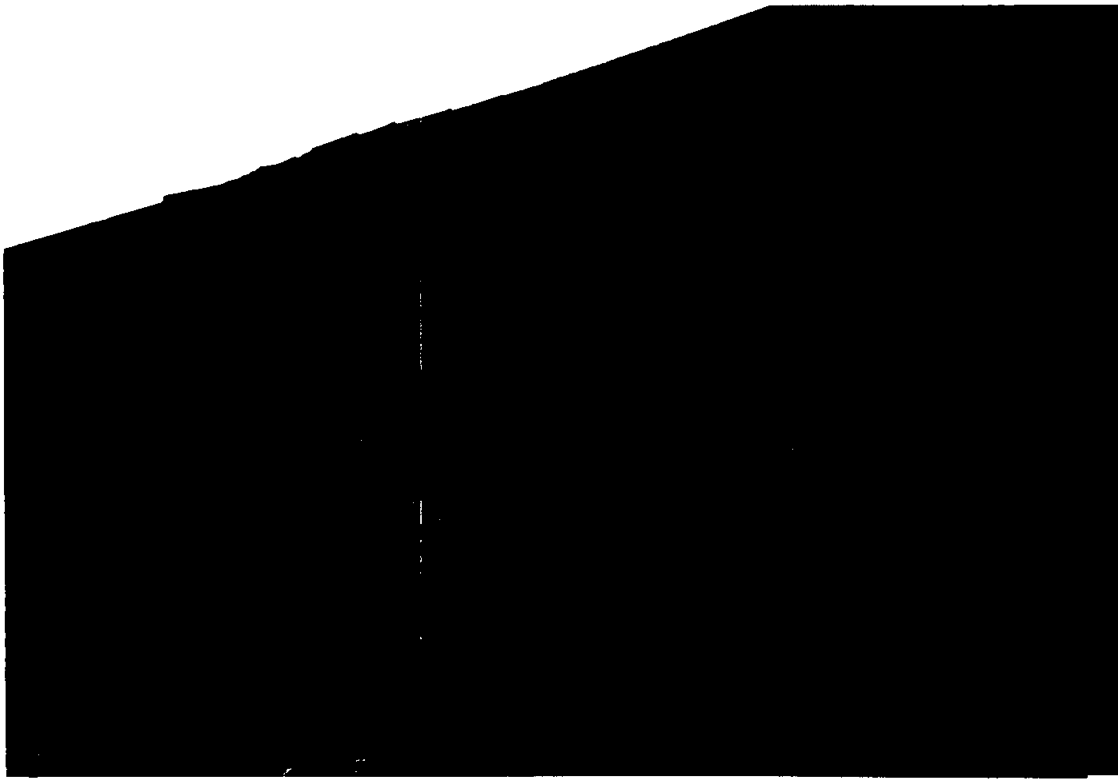
1., 2., 3.: Horizontal chainage, strengthening of the zone under the window, kerb in the upper level
4.: Dowels or cramps to anchor the window posts

Possible remedial actions in the present situation

- Cracks of small width should be filled by injections; for wider ones a proceeding of "unpicking and sewing" should be used
- Horizontal chains at the floor levels (fig. 19e)
- Kerbs should be used at the roof level (fig. 19a)
- Reinforcement of the zone under the windows could be required (fig. 19g)
- Partial recover of the perpendicular wall detachment may be possible prestressing the chains
- Dowels or cramps should be used to anchor the window posts to the structure

Form n°

2



Ston
Building 2, block Ia
Particular of the North façade

The causes of the damage or collapse

In this particular of the North façade (see form 1), almost parallel to the seismic action, the following damage seen in form 1 are highlighted:

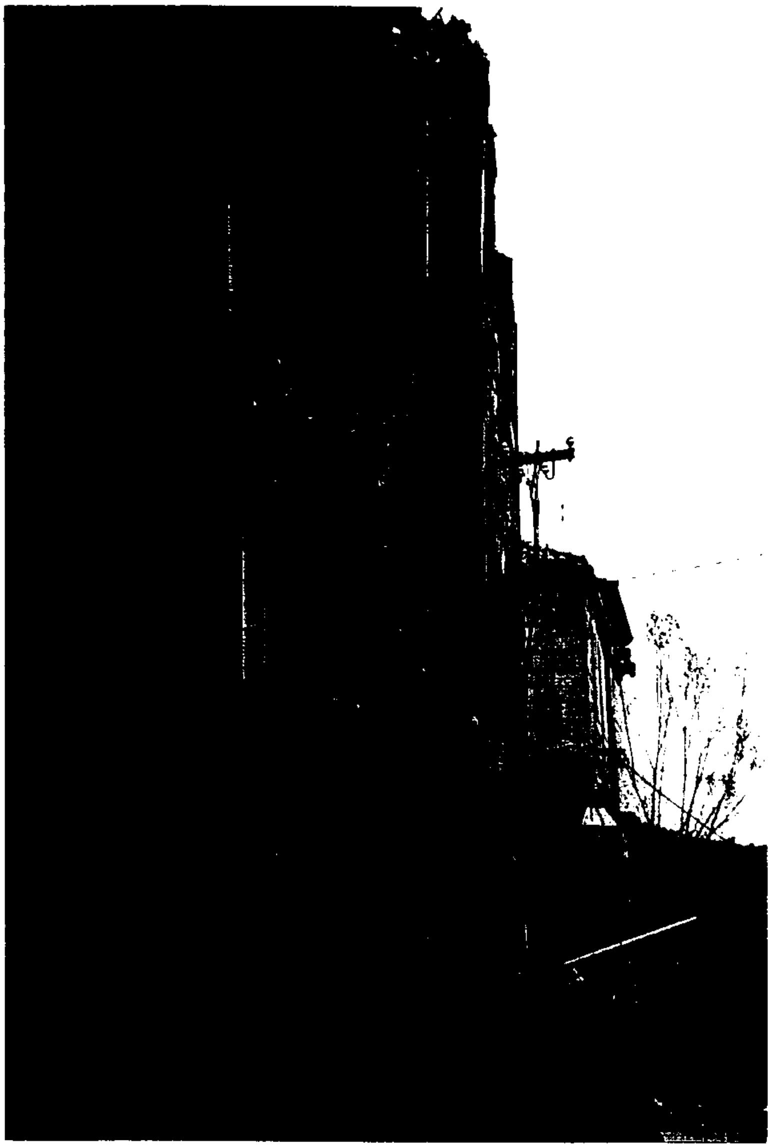
1. Cracks in the zone under and over the windows, showing an independent cantilever flexural behaviour (fig. 13b)
2. Slippage of the window posts

Preventive measures that could have reduced the damage

See form n° 1

Possible remedial actions in the present situation

This picture shows in particular the need to ensure the connection of the window posts and to strengthen the zone under the windows (see form n° 1)



Form n°

Ston
Building 2, block la
Particular of the North façade

3

The causes of the damage or collapse

In this particular of the North façade (see form 1), almost parallel to the seismic action, the following damage seen in form 1 are highlighted:

1. Inclined cracks at the corner (fig. 16)
2. Detachment of the perpendicular wall (fig. 15)

Preventive measures that could have reduced the damage

1., 2., 3.: Horizontal chainage, strengthening of the zone under the window, kerb at the upper level

Possible remedial actions in the present situation

This picture shows in particular the importance of connecting the walls at the corners and possibility to recover part of the detachment of the wall through prestressing.
Cracks should be then injected with grout.

Form n°

4

Ston
Building 2, block Ia
West façade

The causes of the damage or collapse

The West façade is almost perpendicular to the seismic action; typical damage produced by forces acting perpendicularly to the plane of the wall are visible:

1. Detachment of the portion of wall between the roof and the windows (fig. 14); detail in form n° 5, 6
2. Detachment of portion of the external layer of the sack masonry due to the intrinsic weakness of the material
3. Detachment of the window posts and of the lintels

Preventive measures that could have reduced the damage

1.: Strengthening of the zone between the roof and the windows (kerb), connection of the roof to the kerb
2.: Horizontal chainage, strengthening of the zone under the windows; it can be noticed that even the single chain shown in the photo probably has prevented all the wall to fall down
3.: Dowels or cramps to anchor the window posts

Possible remedial actions in the present situation

- Cracks of small width should be filled by injections; for wider ones a proceeding of "unpicking and sewing" should be used
- Injection of the masonry to improve the material resistance
- Reconstruction of part of the masonry with blocks of the same material, after having prepared the area in order to ensure a perfect bond
- Horizontal chains should be used at the floor level (fig. 19e)
- Kerbs should be used at the roof level (fig. 19a)
- Reinforcement of the zone under the windows could be required (fig. 19g)
- Restoring of the roof improving the stiffness in its own plane (fig. 19 h) and assuring connections to the walls (fig. 19c)
- Dowels or cramps could be used to anchor the window posts and the lintels to the structure

Form n°

5

Ston
Building 2, block Ia
Particular of the West façade

The causes of the damage or collapse

In this particular of the West façade (almost perpendicular to the seismic action), the same damage seen in form 4 are shown in detail

Preventive measures that could have reduced the damage

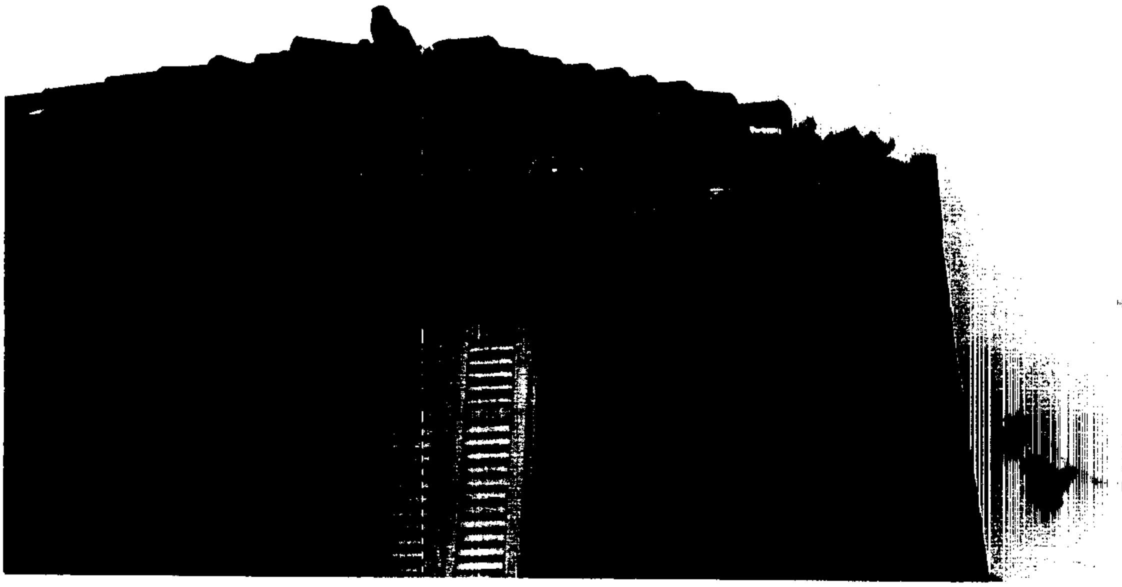
See form n° 4

Possible remedial actions in the present situation

See form n° 4

Form n°

6



Ston
Building 2, block Ia
Particular of the East façade

The causes of the damage or collapse

The East façade is almost perpendicular to the seismic action; the detachment of the portion of wall between the windows and the roof is a damage typically produced by horizontal forces; the shear resistance of this portion of wall was not sufficient to support the horizontal actions transmitted by the roof (fig. 14)

Preventive measures that could have reduced the damage

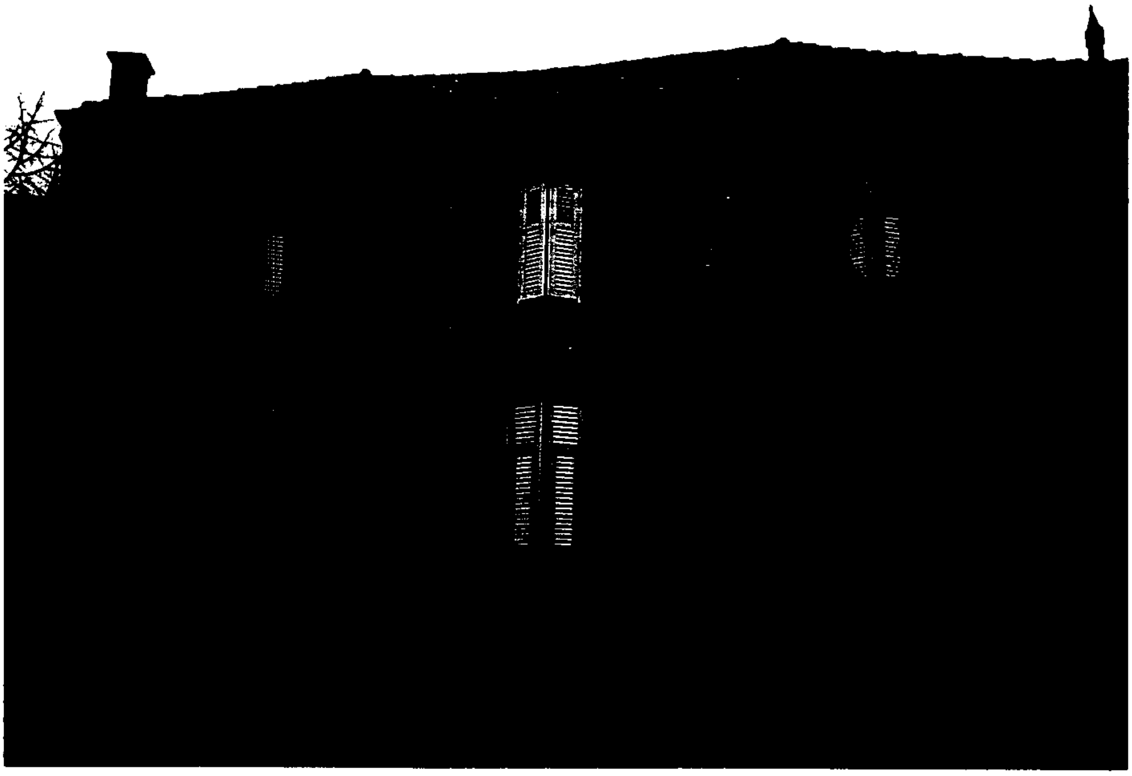
Connection of the roof to the wall (kerb)

Possible remedial actions in the present situation

This photo emphasis the need to realise an horizontal kerb at the roof level (fig. 19a) (see form n° 4)

Form n°

7



Ston
Building 8, block XX
South façade

The causes of the damage or collapse

This building show, as a whole, a good structural behaviour, highlighting that when the masonry fabric is of good quality his typology can bear even high level earthquakes; cracks are concentrated only in the weakest zone that are those under the windows (fig. 13b)

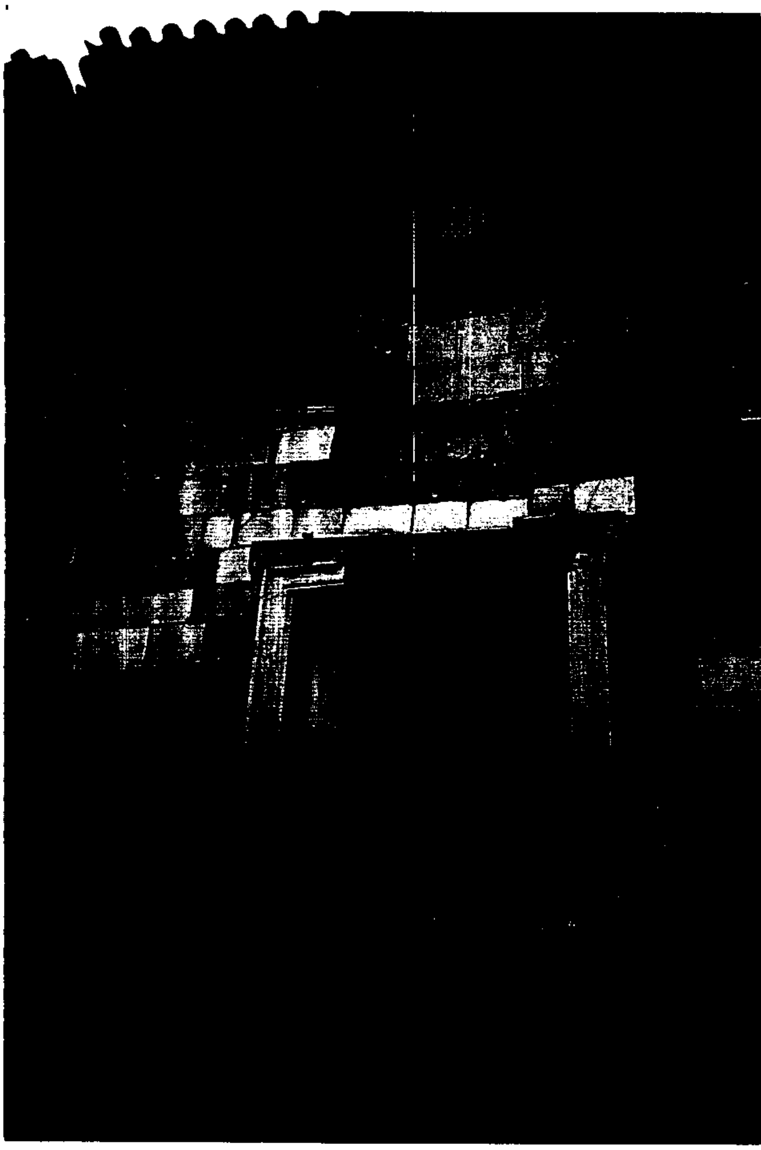
Preventive measures that could have reduced the damage

1.: Horizontal chainage, strengthening of the zone under the window,

Possible remedial actions in the present situation

In relation with the low level of damage the repair measures may be limited

- Cracks should be filled by injections; only in a few zones under the window a proceeding of unpicking and sewing may be required
- Horizontal chains should be used at the floor level (fig. 19e)
- Kerb, even if not indispensable, should be used at the roof level; in this case a very little kerb could be realised, i.e. simply placing one or two steel bars in a concrete or mortar bed (fig. 19a")
- Restoring of the plaster and of the stuccoes



Form n°

8

Ston
Bishop Palace
South Façade

The causes of the damage or collapse

1. The most evident damage is localised in the zones of intrinsic weakness of the wall, i. e. in small band of wall between the roof and the window (fig. 14), and in a portion of wall between the windows, which do not lay on the same vertical line.

2. Cracking and falling of lintels and window post is due to an insufficient connection to the wall

3. Expulsion of stones in the cracked zones is due to an insufficient bond between the facing stones and the filling of the sack masonry, increased by the particular shape of the stones; detail in form n° 9

Preventive measures that could have reduced the damage

1.: Kerb under the roof
2.: Dowels and cramps to anchor the lintels and the window posts
3.: The blocks of the external layer of the wall had also to be anchored through high strength mortar or dowels

Possible remedial actions in the present situation

- Cracks of small width should be filled by injections
- A proceeding of "unpicking and sewing" should be used in the large cracks and in the area where blocks of the external layers suffered relevant outwards movements
- Where big portions of wall are detached, in the area over the window, it is necessary to dismount and to replace the blocks using high strength mortar
- Injection of the masonry or percolating grout to improve the material resistance
- Kerbs should be used at the roof level (fig. 19a)
- Dowels or cramps could be used to anchor the window posts and the lintels to the structure

Form n°

9

Ston
Bishop Palace
Particular of the South façade

The causes of the damage or collapse

In this particular of the South façade expulsion and moving of stones in the cracked zones are highlighted; the picture shows in detail the wedged shape of the facing blocks that facilitate the "expulsion"

Preventive measures that could have reduced the damage

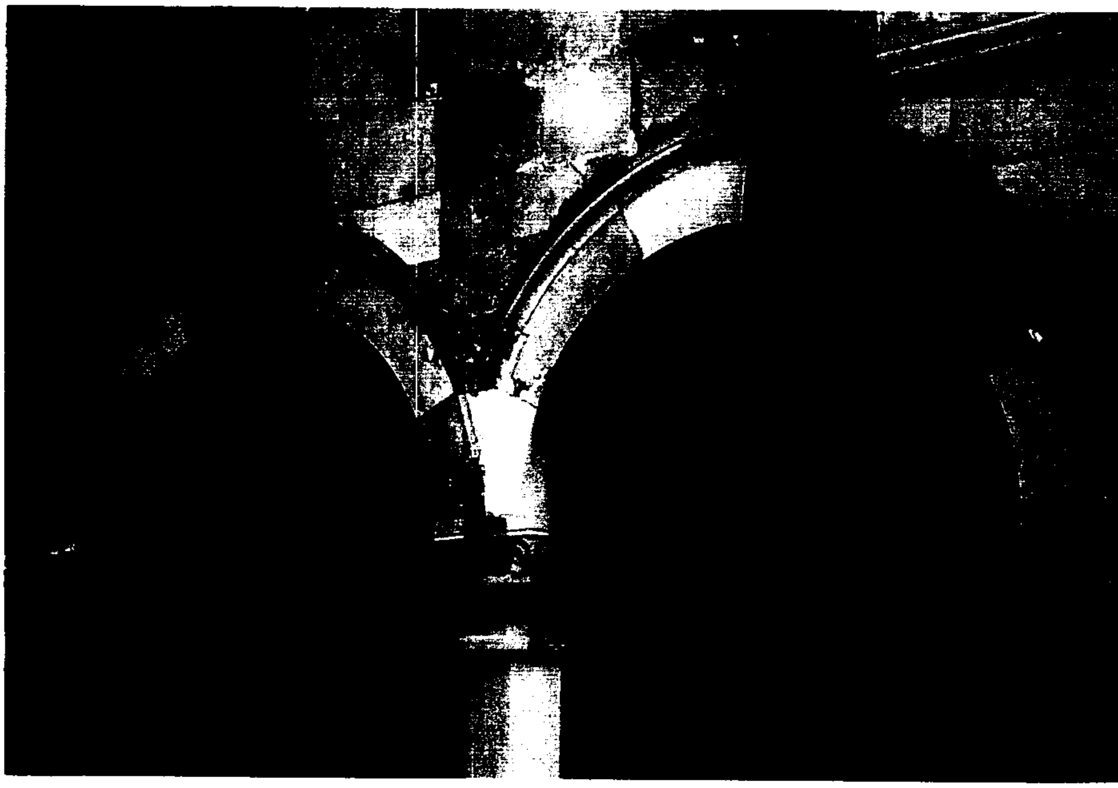
See form n° 8

Possible remedial actions in the present situation

See form n° 8

Form n°

10



Ston
Bishop Palace
Particular of the South façade

The causes of the damage or collapse

In this particular of the South façade it is possible to see the displacement of some stone blocks of the arch due to horizontal movements

Preventive measures that could have reduced the damage

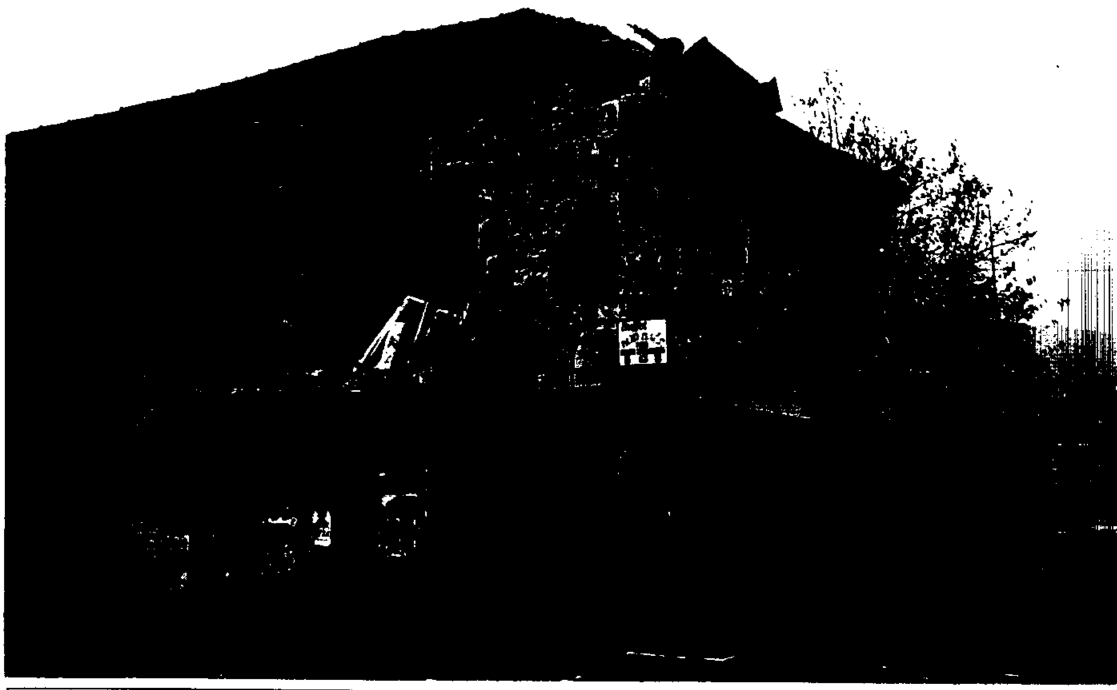
A certain improvement could be have been obtained through horizontal chains

Possible remedial actions in the present situation

- A partial recover of the displacement of some blocks could be obtained by jacks
- Dowels or cramps could be used to anchor some stones to the structure
- Horizontal chains could be used at the floor level (fig. 19e)

Form n°

11



Ston
The Main Guard Building
East and North façade

The causes of the damage or collapse

Many typical damage are visible in this case:

1. Detachment of large portions of wall, due to an intrinsic weakness of the masonry (North façade, in the right of the photo, substantially parallel to the seismic action); see detail in form n°13
2. Detachment of the walls of the East and North façade, due to an insufficient connection of the walls
3. Detachment of portion of the wall between the floor and the roof (East façade, in the left of the photo, substantially perpendicular to the seismic action)
4. Diagonal cracks (East façade); see detail in form n°14
5. Detachment of the window posts and of the lintels (East façade); see detail in form n°14

It must be noticed that all this damage was increased because of the presence of an heavy and very stiff concrete floor at the level of the roof. Besides, it seems like the floor is not connected to the wall in the East façade; that didn't allow the collaboration of the two walls.

Preventive measures that could have reduced the damage

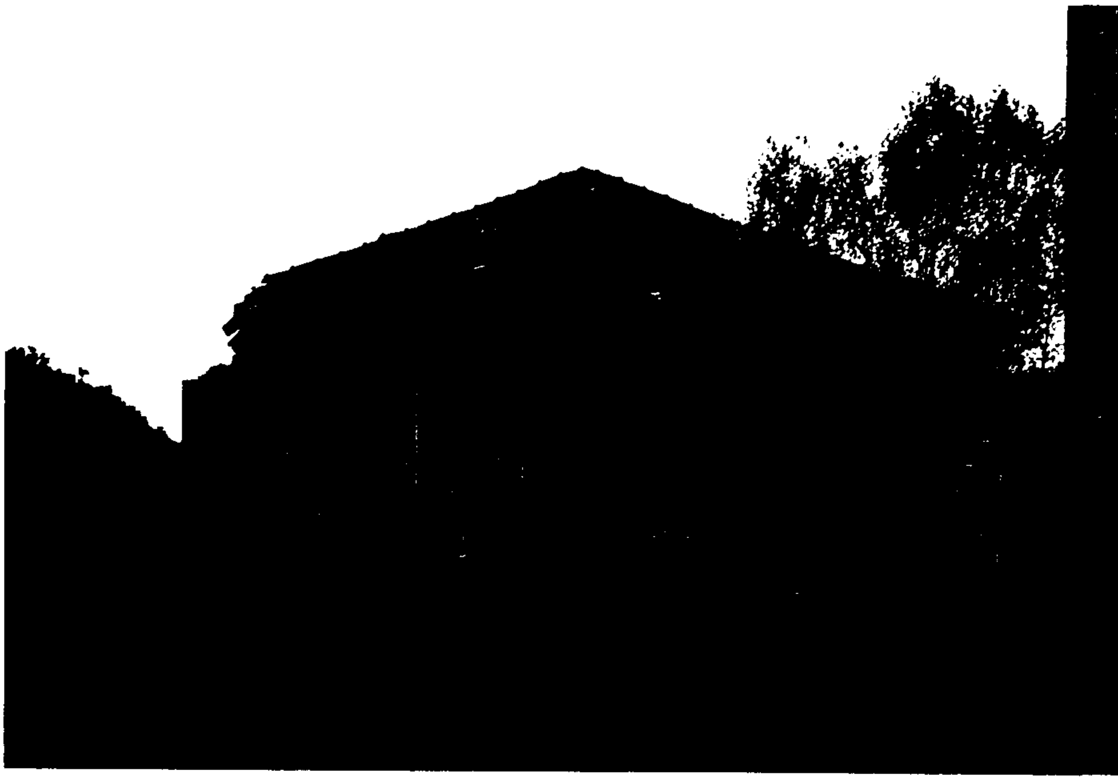
In this case, it seems like the measure adopted in previous restoration didn't get its aim. A softer intervention , consisting in strengthening the material (injection), and creating effective connections among the wall (horizontal chainage, kerb connected to the wall at the roof level), could have probably produced better effects.

Possible remedial actions in the present situation

- Verifying the status of the floor structures and, if necessary, rebuilding them realising good connection with the wall
- Removal or, if possible, propping of the roof
- Rebuilding of the collapsed portion of wall
- A proceeding of "unpicking and sewing" could be used to repair the main cracks
- Horizontal chains should be used at the level of the floor (fig. 19e)
- Kerbs at the roof level (fig. 19a)
- Dowels or cramps could be used to anchor the window posts and the lintels to the structure
- Injection of the masonry or percolating grout to improve the material resistance

Form n°

12



Ston
The Main Guard Building
North façade

The causes of the damage or collapse

In this particular of the North façade some damage mentioned in form 10 are highlighted (detachment of large portions of wall, detachment of the perpendicular East façade)
The detachment of the upper zone at the corner (on the left in the photo) clearly shows that the reinforced concrete floor couldn't assure a good connection between the two walls

Preventive measures that could have reduced the damage

See form n° 11

Possible remedial actions in the present situation

See form n° 11
As regard the corner, it must be evaluated the convenience between dismount and rebuild and to consolidate it after having tried to recover part of the outwards displacement

Form n°

13

Ston
The Main Guard
Building
North façade

The causes of the damage or collapse

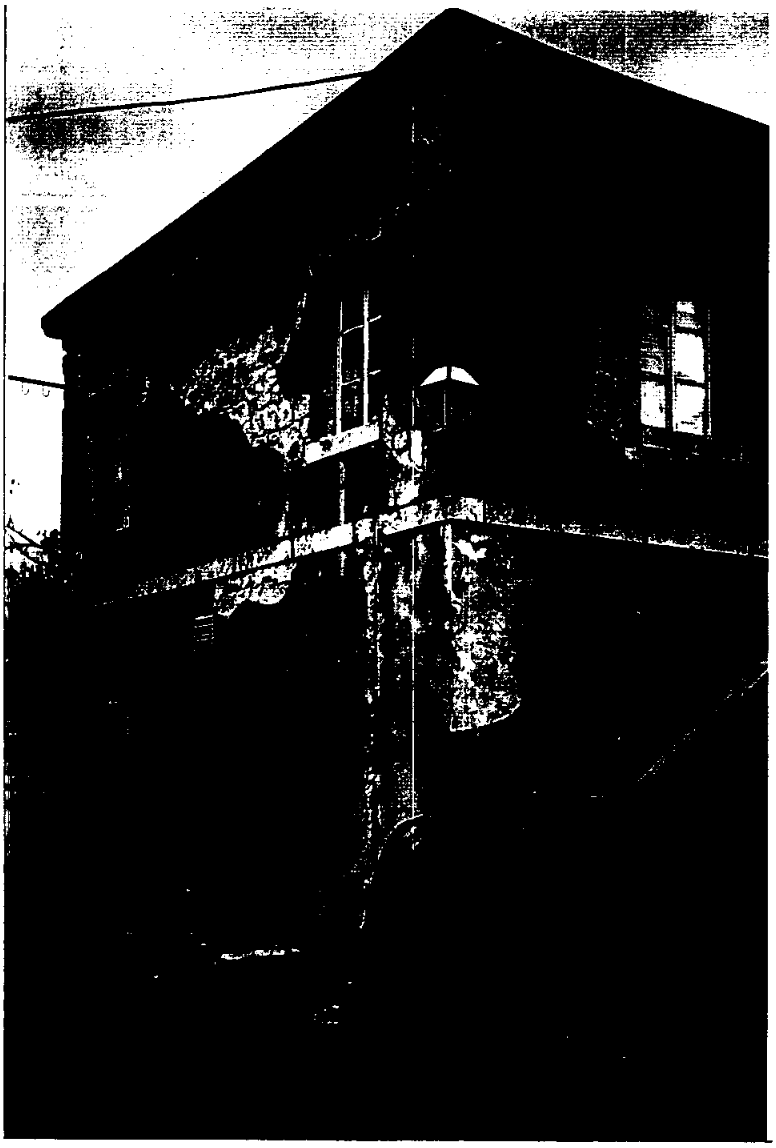
This particular of the North façade shows the presence of the reinforced concrete floor, that (see forms n° 11 and 12) could have increased the ruinous effect of the earthquake due to its weight and to the excessive stiffness respect to the characteristics of the masonry.
Also the poor quality of the masonry is visible.

Preventive measures that could have reduced the damage

See forms n° 11, 12

Possible remedial actions in the present situation

See forms n° 11, 12



Ston
The Main Guard Building
South and East Façade

Form n°

14

The causes of the damage or collapse

1. In this photo diagonal cracks at the corner in correspondence of an upper window of the South façade are visible, and diagonal cracks in the East façade, mentioned in form n° 11, are highlighted.
2. Also detachment of the window posts and of the lintels, due to an insufficient connection to the wall, are visible.

Preventive measures that could have reduced the damage

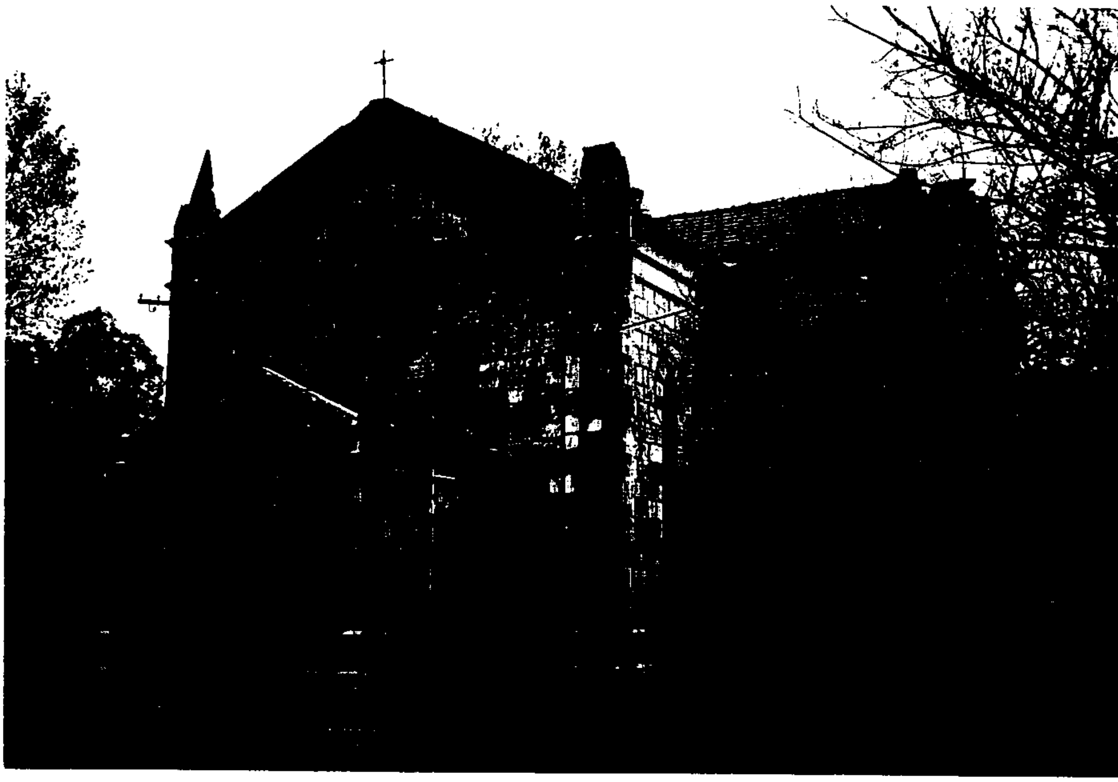
1. Horizontal chainage could have avoided the cracks at the floor level; more difficult is to prevent diagonal cracks in the masonry panel
2. Dowels or cramps to anchor the window post

Possible remedial actions in the present situation

- A proceeding of "unpicking and sewing" could be used to repair the diagonal cracks
- Horizontal chains should be used at the level of the floor (fig. 19e)
- Dowels or cramps could be used to anchor the window posts and the lintels to the structure

Form n°

15



Ston
Parish Church
East and North façade

The causes of the damage or collapse

No ruinous damage was surveyed in the Parish Church.
Considerable cracks were created in the transept (see forms n°16, 17), but they didn't compromise the stability of the walls.
Most of the damage are attributable to insufficient bond of the block stones (forms n°16, 17) and to insufficient connection of non structural elements, as spires or end gable (see detail in form n° 19).

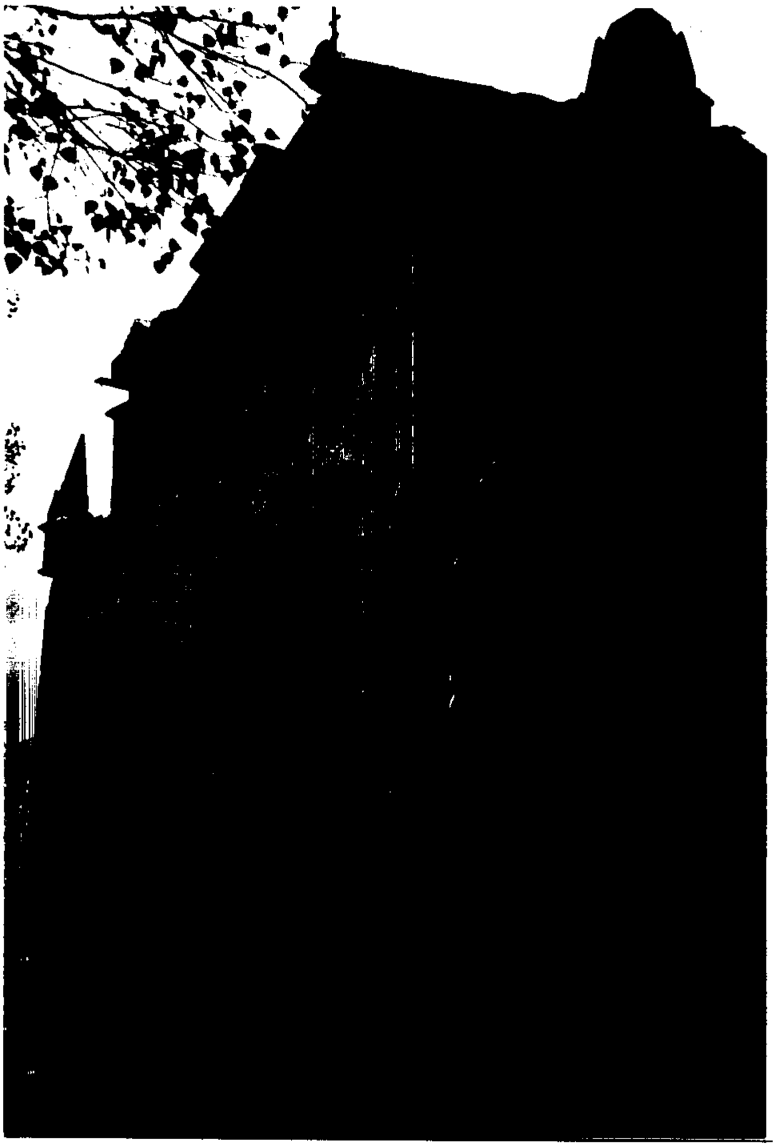
In the photo above only the displacement or falling of the top of some spire is visible; the good quality of the materials and of the construction techniques limited the damage

Preventive measures that could have reduced the damage

See the following forms (16, 18, 19)

Possible remedial actions in the present situation

See the following forms (16, 18, 19)



Ston
The Parish Church
South Façade of the transept

Form n°

16

The causes of the damage or collapse

1. Diagonal cracks are clearly visible (fig. 16)

2. Detachment of stone blocks, and of blocks of the cornice and of the wall rosace are due to an insufficient bond between the stones and the fill

3. The falling of the top of the spire on the right side is due to an insufficient connection of the spire to the structure

Preventive measures that could have reduced the damage

1: Diagonal cracks may probably have been reduced by the presence of an horizontal chainage

2, 3: Dowels or cramps to anchor the blocks and the stone of the spires

Possible remedial actions in the present situation

- A proceeding of "unpicking and sewing" may be used to repair the main cracks; in other cases injections could be a more convenient operation
- Fallen blocks should be replaced, after having prepared the area, using high strength mortar
- Dowels or cramps should be used to anchor the spires to the structure
- An horizontal chainage in the horizontal wall bands

Form n°

17

Ston
The Parish Church
West Façade of the North side of the transept

The causes of the damage or collapse

This façade was damaged substantially in the same way than the previous one

1. Diagonal cracks are clearly visible (fig. 16)

2. Detachment of stone blocks, and of blocks of the wall rosace are due to an insufficient bond between the stones and the fill

3. The displacement of the base of the spire is due to an insufficient connection to the structure

4. The displacement of the key of the arch is due to the horizontal relative movement of the two parts separated by the cracks; see detail in form 18

Preventive measures that could have reduced the damage

1.: See form 16
2., 3.: See form 16
4.: See detail in form 18

Possible remedial actions in the present situation

See form 16
See form 18 for detail on the key of the arch

Form n°

18

Ston
The Parish Church
West Façade of the North side of the transept

The causes of the damage or collapse

This particular of the façade of the transept shows in detail the displacement of the key of the arch, that was due to the horizontal relative movement of the two parts separated by the cracks

Preventive measures that could have reduced the damage

The displacement of the key stone is simply the effect of the loosing of the wall (see form 16); an horizontal chain would have limited or prevented the damage

Possible remedial actions in the present situation

- A partial recover of deformation could be obtained by jacks
- Dowels or cramps could be used to anchor the stone to the structure

Form n°

19

Ston
Parish Church
West façade

The causes of the damage or collapse

This particular of the North façade clearly shows the lack of connection of non structural element to the structure.

The end gable worked as free cantilever during the shake, so that an insufficient connection produced its collapse

The base of the spire was disconnected by the shake, and the top of the spire twisted on it. Also in this case an insufficient connection was responsible of the displacement

Preventive measures that could have reduced the damage

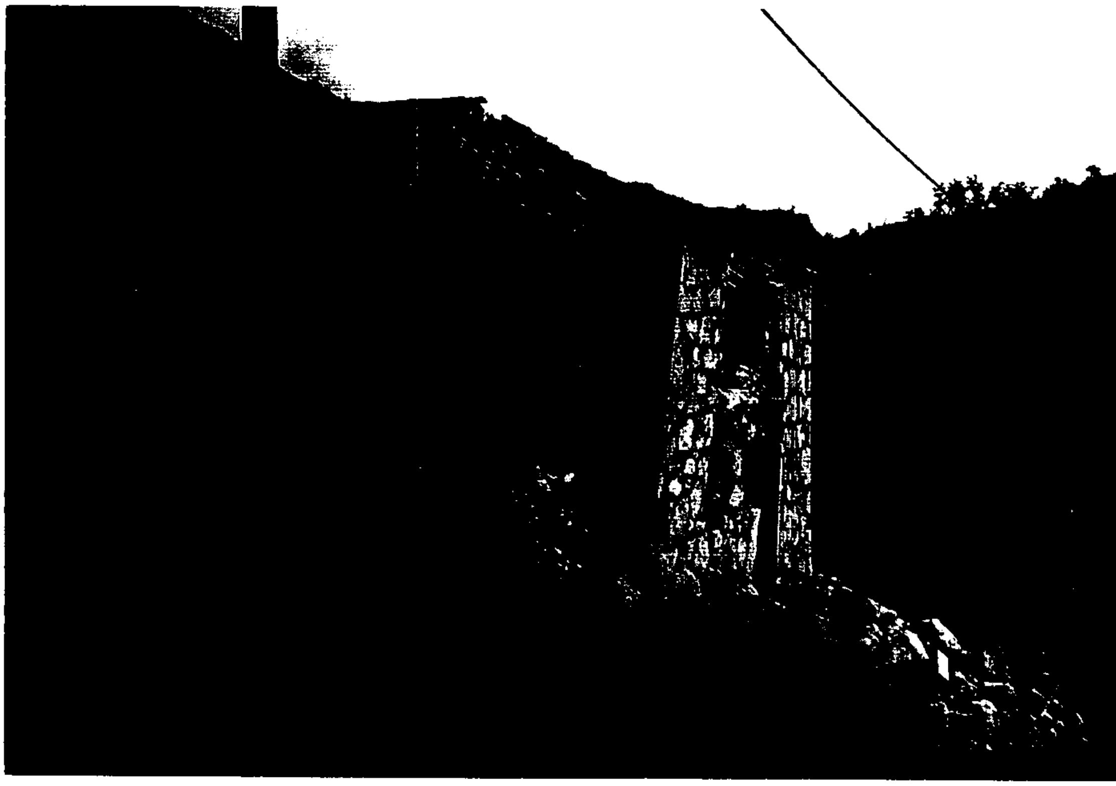
A check-up of the connections and, where insufficient, their improvement with dowels, stirrups or cramps could have prevented damage and collapses.

Possible remedial actions in the present situation

- Dowels, cramps or stirrups could be used to connect the spire to basement and the basement to the structure.

It must be paid attention, when introducing dowels or cramps (protected against the corrosion), to realise connection able to avoid the rotation of the top of the spire
Also the rebuild end gable will be connected by dowels or cramps to the gable

- Injections or percolating grout at the base of the spire



Form n°

20

Trnova
North and West façade of a farm

The causes of the damage or collapse

In the building shown in the picture the typical damage surveyed on the farms of the villages struck by the earthquake are visible . The quality of the materials and the construction techniques are in these cases rather poor, so that the effects of the earthquakes were often ruinous.

The following damage are visible:
1. Detachment of the two perpendicular walls at the corner (fig. 15); it must be noticed that the presence of a chain (see detail in form n° 22) has probably avoided the complete collapse of the wall of the west façade, on the right of the photo)
2. Detachment of the portion of wall between the roof and the windows (fig. 14); detail in form n° 21,
3. Detachment of portion of wall due to the intrinsic weakness of the material; detail in form n° 22
4. Falling of part of the roof, not enough connected to the structure; detail in form n° 21

Preventive measures that could have reduced the damage

1.: Improvement of the connection between the walls (kerb at the roof level, improvement of the horizontal chainage)
2.: Kerb at the roof level
3.: Percolating grout could have improved the resistance of this very poor kind masonry
4.: Connection of the roof to the walls through a kerb

Possible remedial actions in the present situation

- Reconstruction of the collapsed masonry
- Injections or percolating grout of the masonry to improve the material resistance
- Horizontal chains should be used at the floor level (fig. 19e)
- Reinforced concrete kerb should be used at the roof level (fig. 19a)
- Restoring of the roof improving the stiffness in its own plane (fig. 19h) and assuring connections to the walls through the kerb (fig. 19c)

Form n°

21

Trnova
West façade of a farm

The causes of the damage or collapse

In this particular of the west façade, almost perpendicular to the seismic action, some damage mentioned in the form 20 are highlighted; in particular, it is possible to see the complete detachment of the portion of wall between the roof and the windows (fig. 14), the falling of part of the roof and its disconnected structure.

Preventive measures that could have reduced the damage

See form n° 20

Possible remedial actions in the present situation

See form n° 20

Trnova
West façade of a farm

Form n°

22

The causes of the damage or collapse

In this particular of the west façade the rather poor quality of the masonry is highlighted; in particular the chaotic structure of the filling is visible, and the consequent lack of connection between the external layer of the wall and the filling itself (collapse of the facing stones at the corner of the door, cracks on the left side of window).

The horizontal chain that probably avoided the complete collapse of the wall is also visible.

Preventive measures that could have reduced the damage

See form n° 20

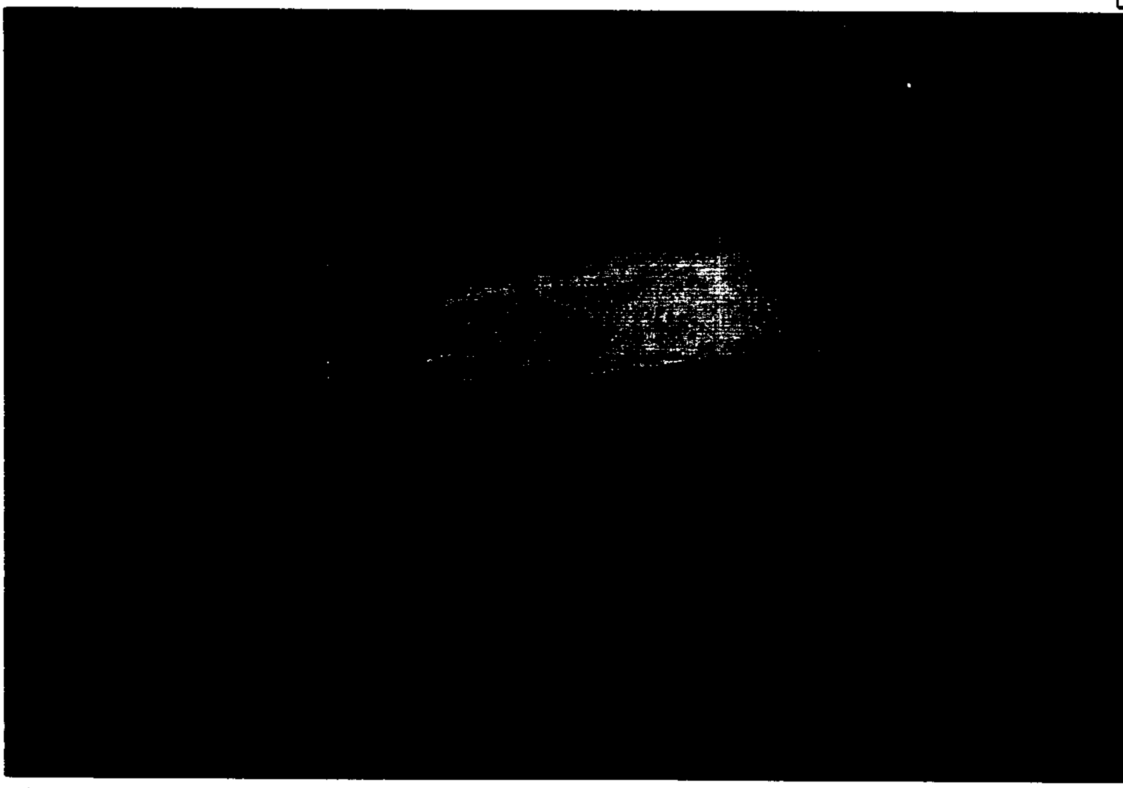
Possible remedial actions in the present situation

See form n° 20

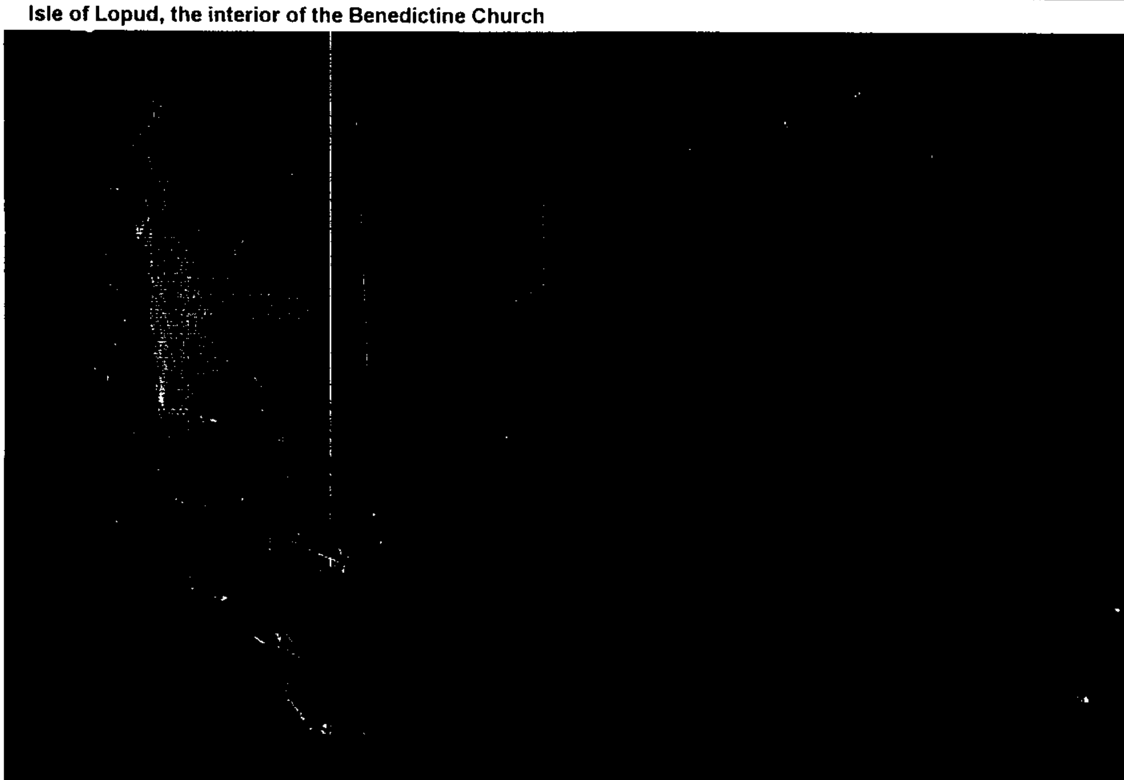
Example of insufficient connection of artistic decorations

Form n°

23



Isle of Lopud, the interior of the Benedictine Church

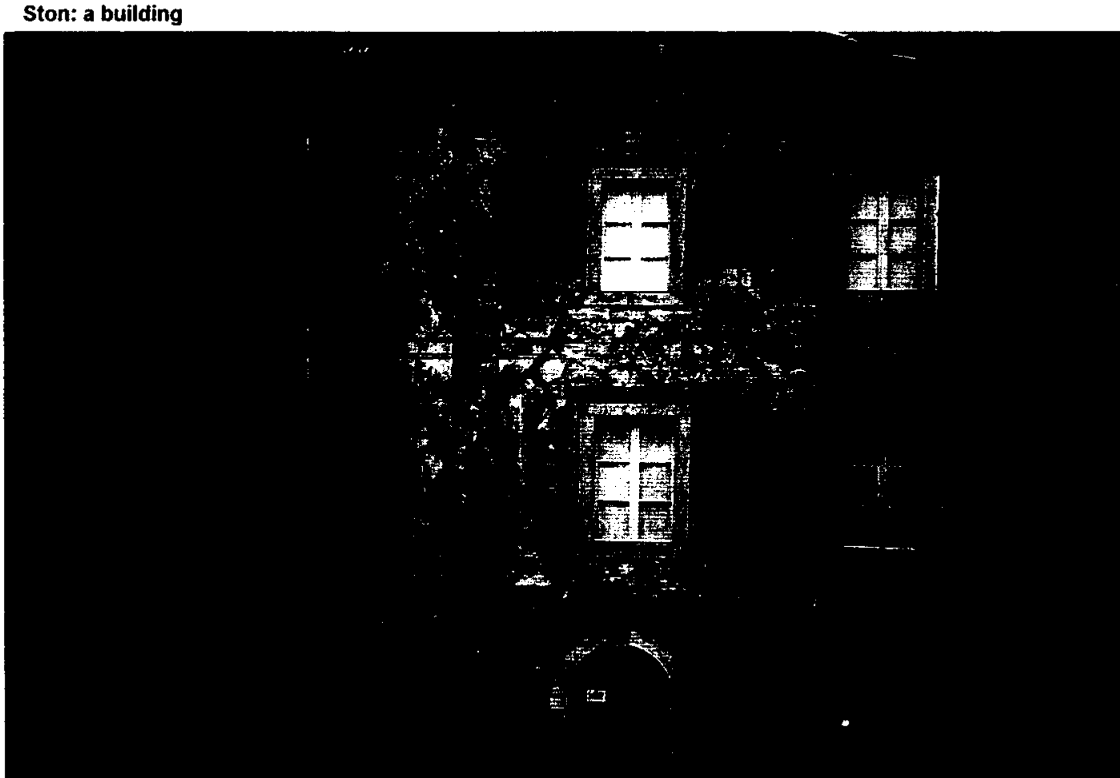


Isle of Lopud, the interior of the Benedictine Church

These case shows the collapse of non structural decorative elements; it is clear that the connection, realised only with a few cramps, was absolutely insufficient. In these cases a systematic control of the connection is required to prevent damage.

Examples of buildings performing a good structural behaviour	Form n° 24

Ston: a building



Ston: building 4, block VII

Both the buildings shown in these photos suffered just a few cracks, and their global stability was not compromised.

This confirms that when the building is realised with good materials, when a good technique of construction is respected, and when the collaboration between the walls is ensured -e. g. using horizontal chains- clearly visible in the photos, this typology of building can well perform even in case of a strong earthquake.

Detachment of the zone under the roof

Form n°

25

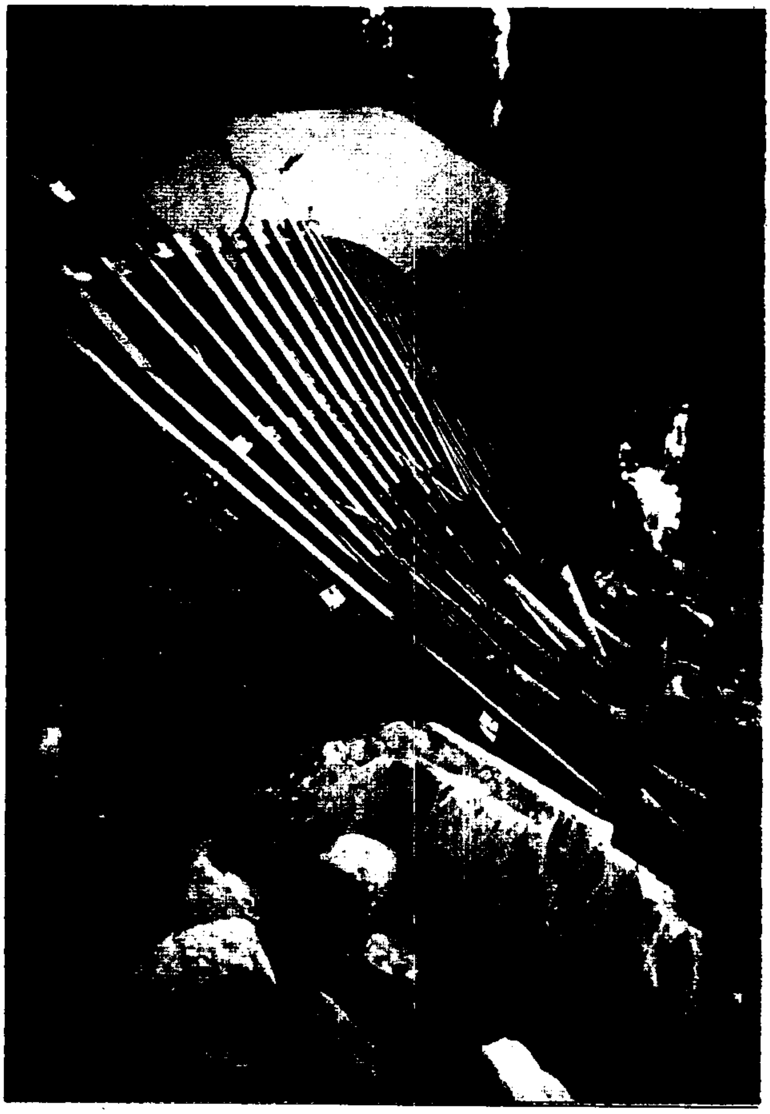
Ston: example of detachment of the whole zone between the roof and the windows

Ston: example of detachment of a small band under the roof

These photos show a kind of damage frequently surveyed (forms n° 4, 6, 21).

If the horizontal band under the roof is not enough resistant, the horizontal component of the seismic force acting perpendicularly to the wall, added to the thrust of the roof, can produce the collapse of the band (upper photo, fig. 14).

Collapse can be confined to the zone of the support of the roof when the band is sufficiently large and the masonry is of good quality (lower photo)



The horizontal slippage of the roof, is a phenomenon that often occurred, due to the lack of connection between it and the walls.

In these cases a stiffening of the roof in its own plane (fig. 19h), a good connection of the roof to an horizontal kerb (fig. 19c) and of the kerb to the wall (fig. 19a) should have prevented this kind of damage.

The church of Mavrinca

The church of Mavrinca

Insufficiency of a preventive measure (reinforced concrete kerb)

Form n°

27

These photo show the collapse occurred in a house of Trnova recently restored with the realisation of a reinforced concrete kerb at the roof level.

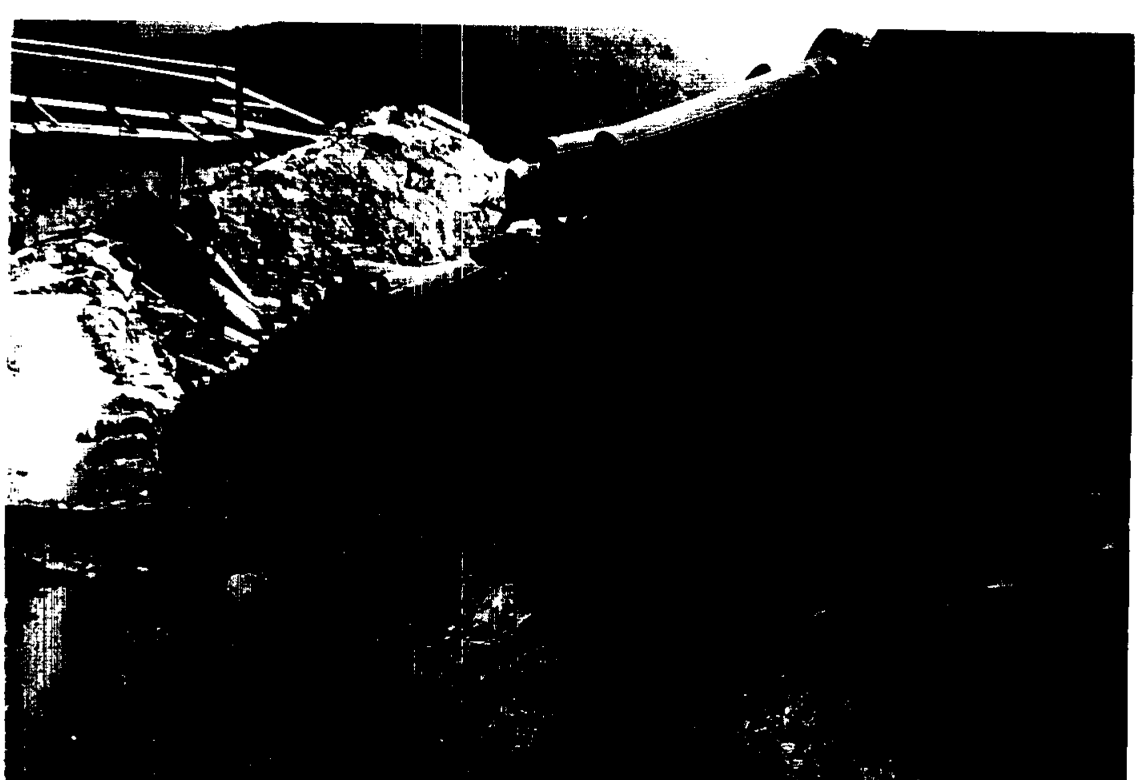
Some deficiency of the interventions made this measure ineffective.

1. The roof was not connected to the kerb; this didn't permit to avoid the slippage of the roof

2. The kerb was simply leaning on the wall without connection; besides the masonry was clearly of poor quality

3. The kerb didn't assure a good connection of the walls, being realised only on the two lateral walls

Particular of a house of Trnova



Particular of a house of Trnova

Detachment of the corners

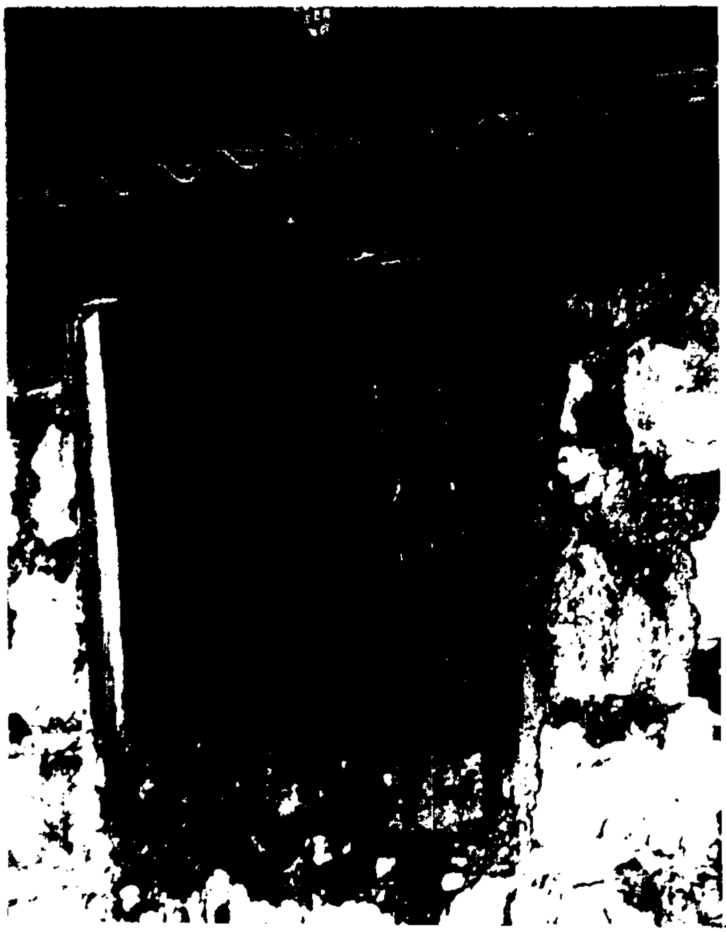
Form n°

28

The detachment of the corner is a type of damage frequently occurring, due to both the components of the seismic actions parallel (cross cracks) and perpendicular (thrust due to he arch effect) to the walls.

Ruins of a house of Trnova

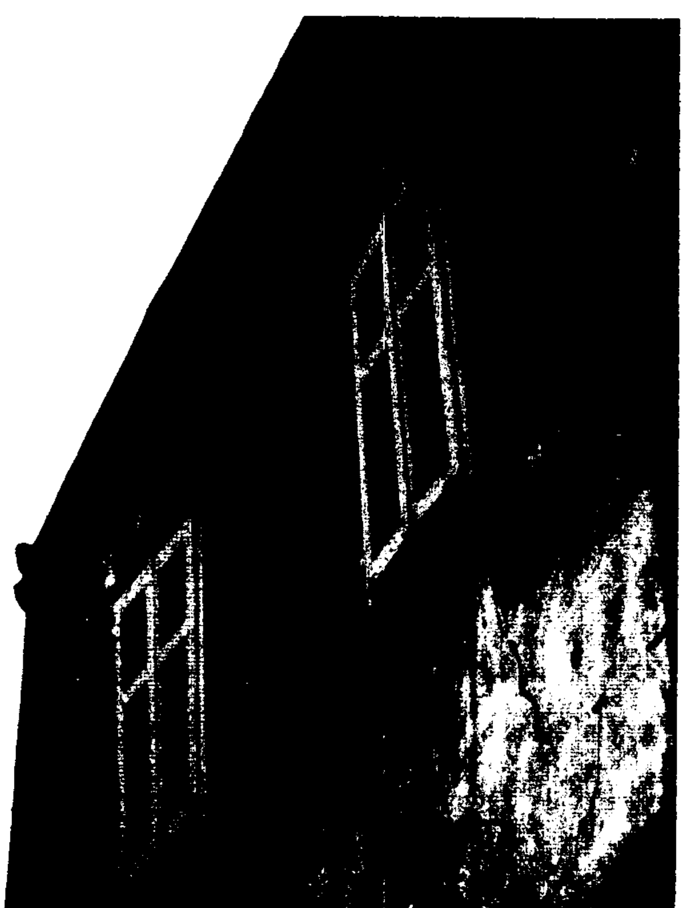
A house of Mavrinca



In these cases it is necessary to dismount and replace the displaced elements and then to fix them with cramps

Particular of a house of Trnova

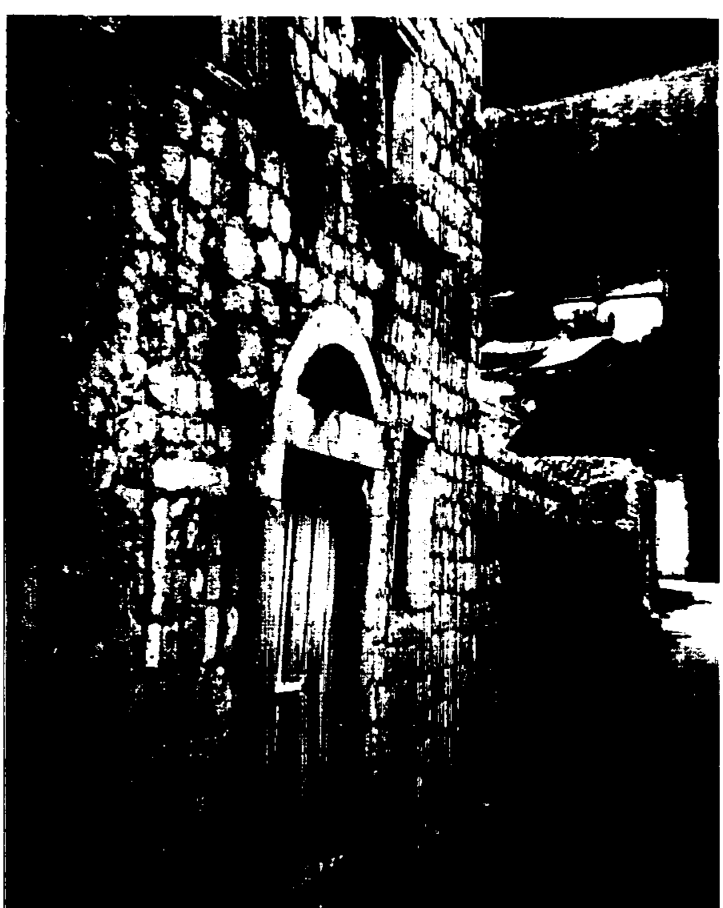
Particular of a house of Ston



In these cases a partial recover of the displacement could be obtained using tie bars or jacks (see fig. 18). Subsequent injections and chainage will ensure the stability of the wall.

When the masonry is rather disconnected it must be evaluated the convenience to dismount and rebuild the damaged portion of wall.

Particular of a house of Ston

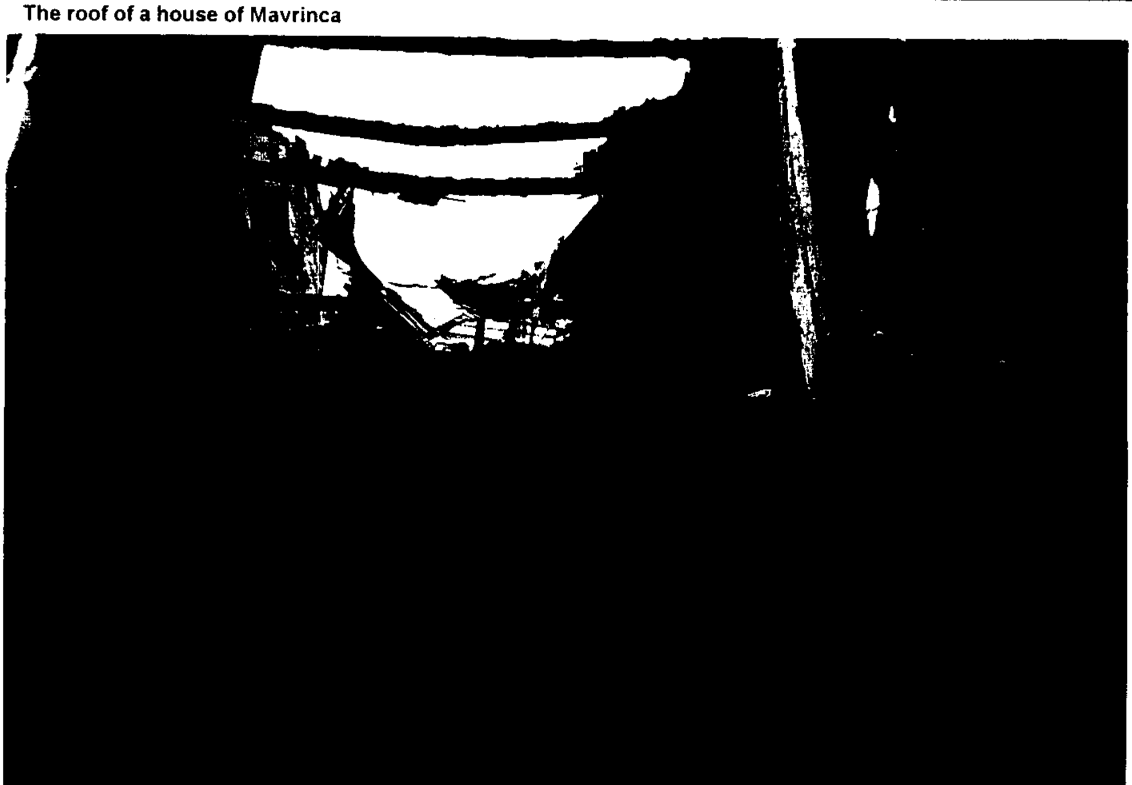


Particular of a house of Ston

Inappropriate timber structures

Form n° **31**

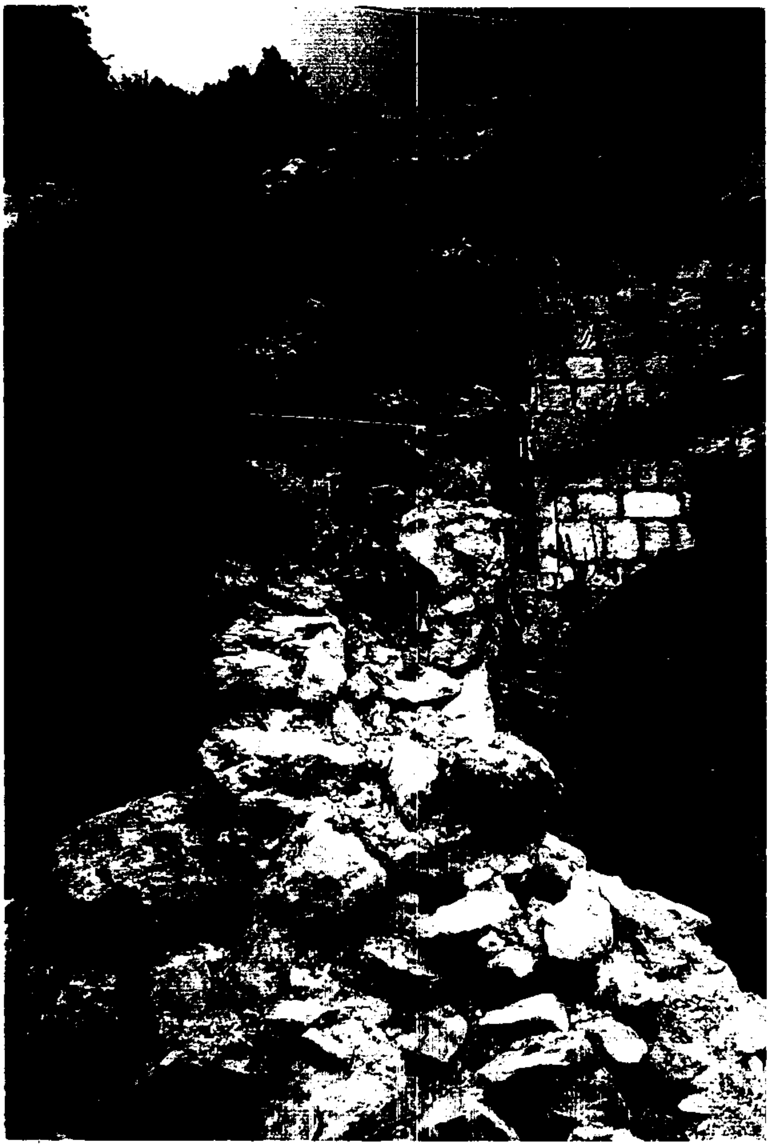
The roof of a house of Mavrinca



The wood floor of a house of Ston

The upper photo shows an elementary roof without any connection with the walls -and in particular with the tympanum of the building- realised with simple rafters completely disconnected each other.

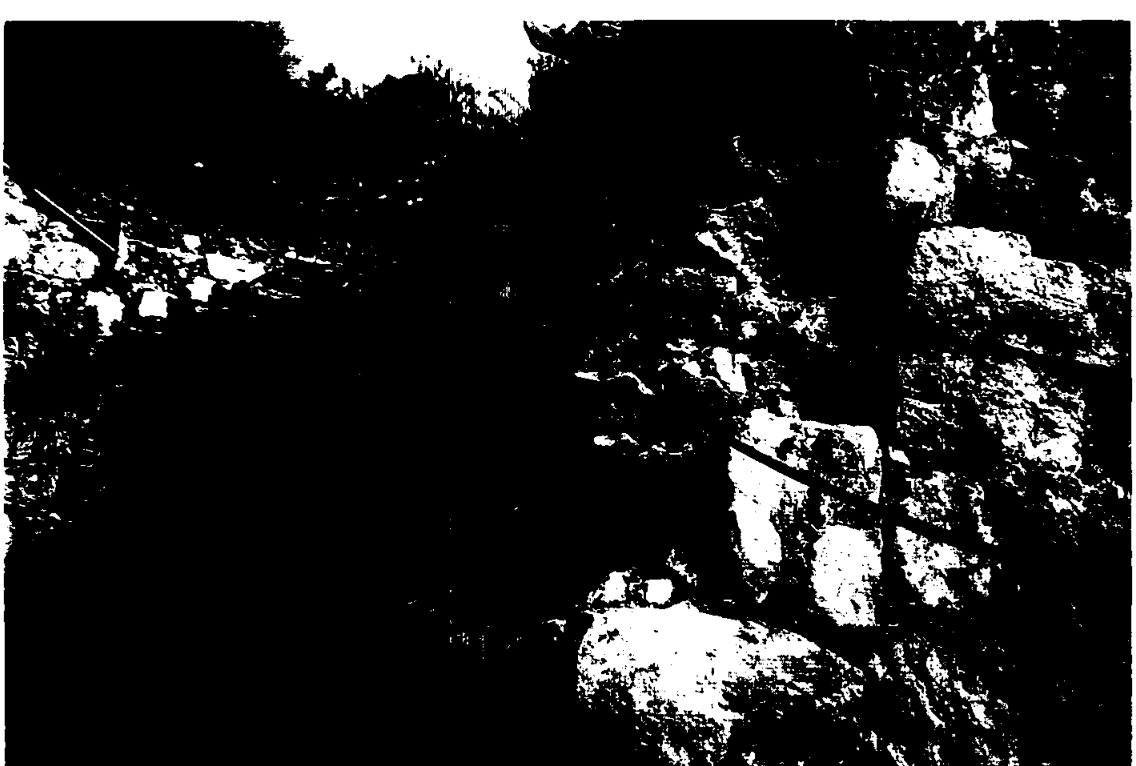
In the lower photo extreme decay compromised the stability of the timber floor; the latter didn't provide any structural collaboration with the building.



Typical sack masonry with poor quality mortar do not ensure the cohesion of the wall.

In the lower photo is particularly evident the lack of bond and the detachment of the external stone layer

Particular of a house of Trnova



Particular of a house of Trnova

4. POSSIBLE REMEDIAL ACTIONS

4.1 Generally

On the basis of what discussed in chapter above the restoration criteria can be synthesised as follows.

4.2 The wall as a material

The following measures can be adopted according with the different type of damage.

a) Sack masonry with loose material (forms n° 22, 27, 32)
- Injections of the masonry.

b) Detachment of single façade blocks (forms n° 9, 16, 17)
- Injection of the masonry
- Replacement with blocks of the same material (or with the fallen blocks) assuring sufficient connection.

c) Collapse of portion of walls (forms n° 5, 12)
- Injections of the masonry
- Removal of disconnected façade block
- Restoring of the sack masonry with blocks of the same material (or with the fallen blocks) assuring sufficient connection

d) Blocks that moved without falling down (form n° 9, 29)
- Removal of the displaced blocks
- Removal of the mortar
- Restoring of the displaced blocks assuring sufficient connection.

e) Moved or fallen lintels, jamb or window post (form 2, 29)
- Replacement with elements of the same material when it is not possible to utilise the original ones
- Anchorage of the elements with cramps or dowels.

Injections, when it is possible, may be substituted by grout percolating from the top of the wall; this operation is much cheaper than injections. As regard the material, when there are not frescoes or valuable plasters, cement grout can provide good results, and is the cheaper to be used.

4.3. The wall as a structure

Apart from the cases of collapse of portions of the wall, whose reconstruction was synthesised in the paragraph above, the main damage is represented by cracks and/or deformations.

Cracks can usually be filled with grout (percolating or injections), or, when the width is too large, some technique of "unpicking and sewing" can be employed.

As regard the *deformations* and outwards inclination, according with different situation, 3 possibilities may be considered:

a) To maintain the deformation as it is, if it doesn't affect the overall stability; the stability, however, can be improved through chains, as it'll be discussed below.

b) To recover part of the deformation through jacks or provisional tie bars (fig. 18, form n° 30)

c) To dismount and rebuild part of the wall (form n° 30)

All these measures, anyway, usually reproduce a situation similar to the original, even if with improved characteristics, but they don't provide any substantial strengthening; on this purpose it is usually necessary to act through a series of chainages and reinforcements that can be described as follows. The choice of the measure to be adopted depends on the state of damage and on the intrinsic characteristics of the building.

a) Insertion of horizontal chains at the level of the floors to connect the walls.

b) Realisation of a kind of "kerb" (fig. 19a) at the level of the roof to connect the upper part of the walls (fig. 19b) and to connect the roof to the main walls (fig. 19c). This "kerb" may be made up in two ways:

- removing from the inside a corner of stones and replacing them with a reinforced concrete kerb (fig. 19a')
- just inserting some chains in the middle of the sack masonry having locally substituted the ancient mortar with new cement mortar (fig. 19a")

c) Insertion of a steel frame in the zone under the window in order to strengthen these weak zone (fig 19g), and to permit the developing, as regard the actions in the plane of the wall, of the more resistant "shear type behaviour" (fig. 13)

d) Insertion of vertical cables, eventually prestressed, in the wall (fig. 19f)

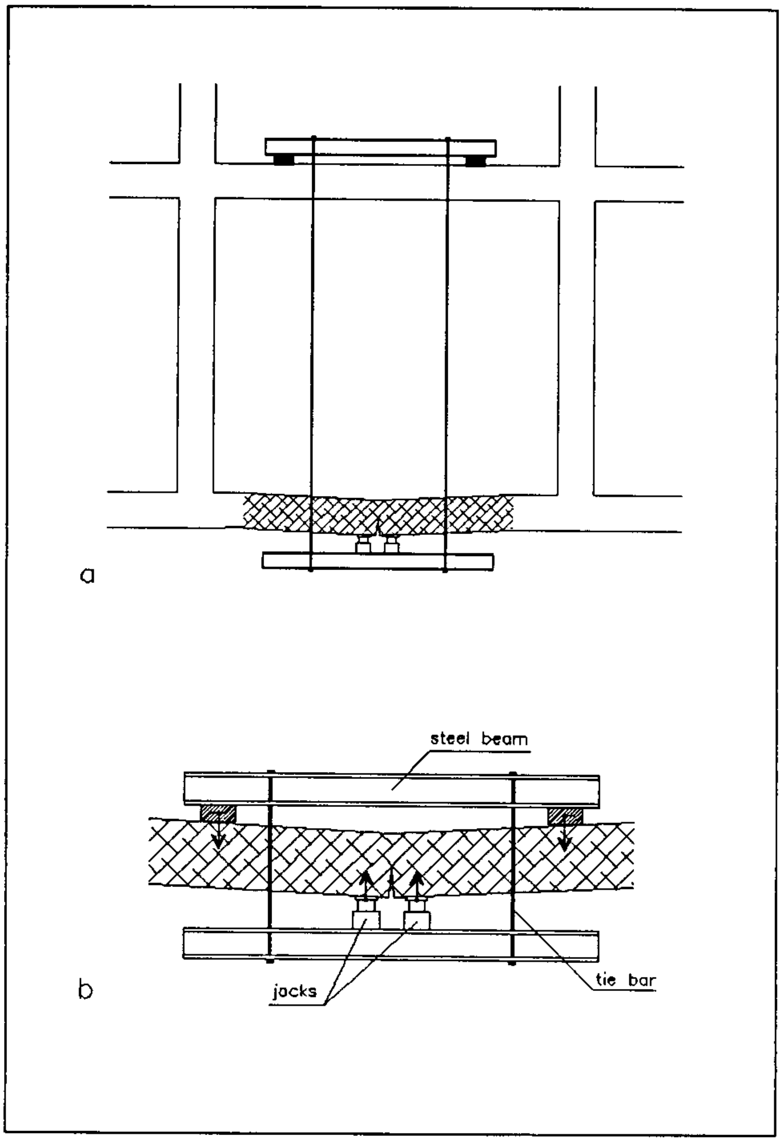
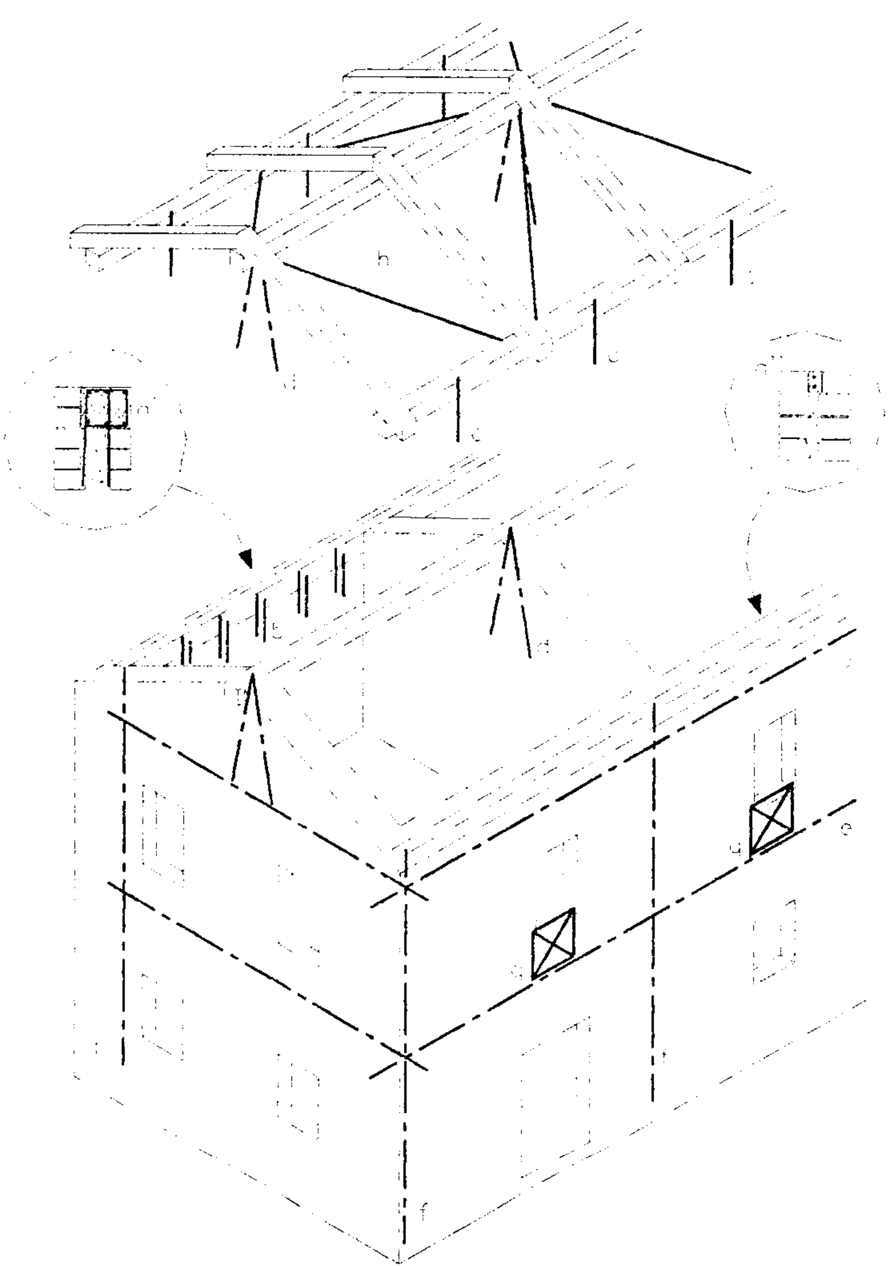


Fig. 18 Intervention to recover the wall deformation



a.: Reinforced concrete kerb at the top of the walls
b.: Bars to connect the kerb to the masonry
c.: Dowels to connect the roof to the kerb
d.: Dowels to connect the ridge beam to the tympanum
e.: Horizontal tie rods
f.: Vertical tie rods
g.: Steel frames to stiffen the zones under the windows
h: Steel bars or cables or wood struts to stiffen the roof

Fig. 19 Scheme of interventions on a masonry building

4.4. Floors

Two functions are mainly required to the floors: to improve the structural behaviour of the building as regard the horizontal actions and to bear the vertical loads acting on them.

a) Horizontal actions

As regard the horizontal actions the floor should be stiff enough and well connected to the walls; if these conditions are respected, the capability to develop a "vertical arch effect" in the wall is increased, the detachment of the façade is prevented and deformations due to torsional effects are reduced.

It must be noticed that torsional effects are more evident if the building is asymmetric or inserted in an asymmetric block.

The following interventions can be chosen to improve the stiffness of the floors:

- realisation of a second order of planks perpendicular to the original one
- introduction of steel bars on the perimeter of the floor, and of plates crossing the floor (fig. 20).

Different kinds of connection can be used to join the floor with the walls.

Concrete floors not only are against the historical conception of these type of buildings, but also from the static point of view there are not clear advantages; what can be required from a floor structure in seismic zone is an increased stiffness but that, as it was said, can be obtained also in wood floors.

It must be pointed out, on the contrary, that a bigger mass increases the inertia forces and a too high stiffness does not allow little adjustments necessary to redistribute the stresses in a masonry structures.

To maintain the original structural conception has also the advantage of not reducing the cohesion of the wall not being necessary to realise new holes for the insertion of new beams.

b) Vertical actions

Vertical actions are generally a secondary aspect of the seismic actions.

Often, strengthening of the floor structure is required when the building is designed for new functions or the loads increase; in these cases thin concrete slabs may increase the strength of the original timber structure, or, more radically, new steel floor beams may be required. Anyway, such interventions must be carefully considered as they involves an alteration of the original conception and of the historical value of the building.

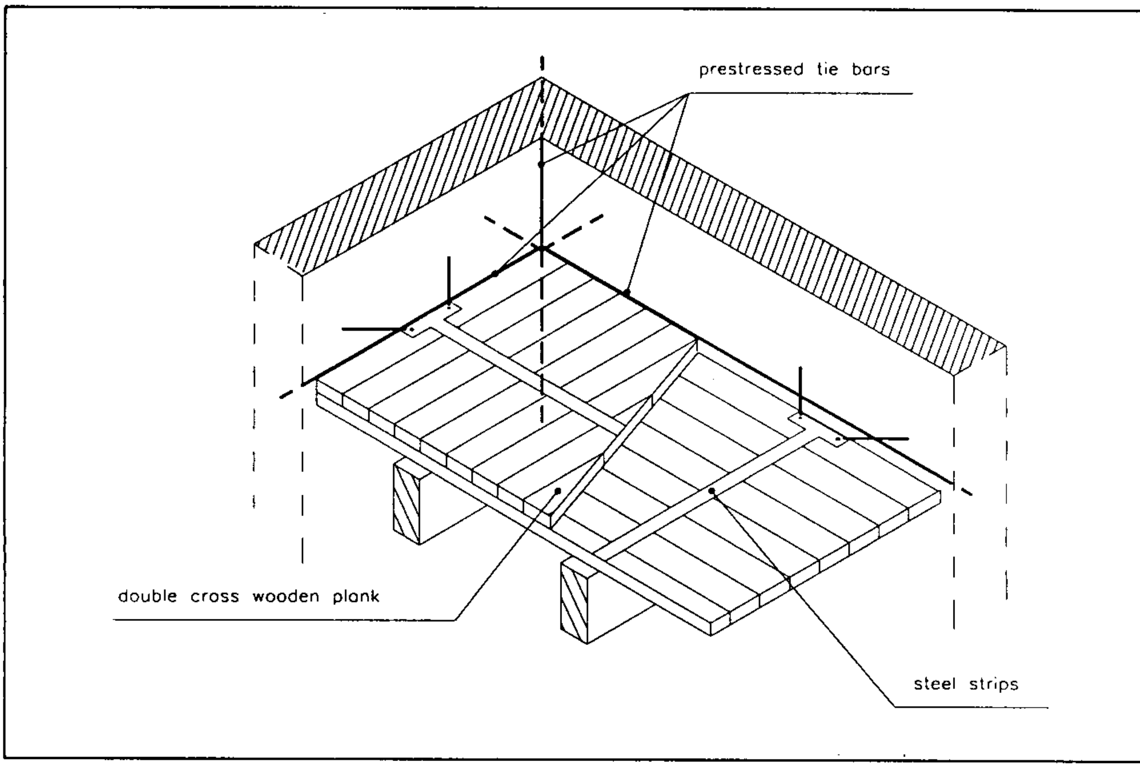


Fig. 20 Intervention to increase the stiffness of a wood floor

4.5 Roofs

A regard the roofs, the timber structures not only can be maintained, but usually, due to their weight, are more favourable for the general stability than new reinforced roofs.

Surely some specific measures must be taken because the current way as they are realised is absolutely inadequate.

There are three conditions to be fulfilled.

a) The ridge beam should be well anchored to the tympanum (fig. 19d), and the lateral edge beams should be well anchored to the "kerbs" (fig. 19c). The latter, as described in § 4.3, must be well connected to the main walls.

b) The roof must have an appropriate stiffness in its own plane.

This condition is very important because the connection on the top of the walls is fundamental to permit the collaboration of the perpendicular walls and because the roofs, for their intrinsic constitution, are more deformable than floors.

The stiffening can be obtained introducing a new order of plank, or, more easily, with crossing stiffening elements (steel bars or cables, or wood struts bars) between the main beams of the roof.

c) The horizontal thrust of the roof must be eliminated through horizontal chains, usually made of steel or wood.

4.6. Non structural elements

Non structural element as cornices, entablatures, ridges, spires, must be well anchored to the structure using dowels or cramps.

5. CONCLUSIONS

Even if largely damaged, most part of the buildings can be restored; the earthquake could produce in many cases so large damage and collapses because of the decay of materials, and because of the imperfections on the structural conceptions, mainly as regard the connections between the walls, floors and roof.

What is important now is to follow appropriate criteria that should be, at the same time, reasonable and easy to realise utilising traditional techniques and materials.

In this way the precious historical value may be maintained for the future generations.