Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 77 (1998)

Artikel: War and earthquake damage in Dubrovnik: preventive and remedial measures

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DOI: https://doi.org/10.5169/seals-58279

War and Earthquake Damage in Dubrovnik: Preventive and Remedial Measures

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Giorgio Croci, born 1936, has carried out much research into, and many important projects for the restoration of historical buildings such as the Colosseum and the Senatorio Palace in Rome, the Tower of Pisa and, following the recent earthquake in Assisi, the Basilica of S. Francis. He is a consultant for the Council of Europe and for UNESCO.

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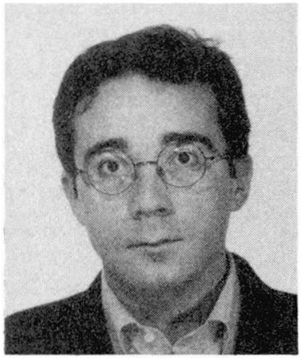

Alessandro Bonci, born 1968, graduated in civil engineering at the University "La Sapienza" in 1995. Since then he has been involved with various restoration projects and as an adviser for UNESCO. He's now working on UE research concerned with new technologies for the seismic protection of historic buildings

Summary

In the historic towns of Dubrovnik and Ston, building dating back up to the 14th century, , suffered major damage during the recent war and were then subsequently struck by a strong earthquake in September 1996; Because of the exceptional value of the sites, UNESCO organised several missions which involved Prof. G. Croci. This paper summarises the studies carried out after a detailed survey which sought to examine the structural behaviour of the buildings and the relationship between local construction techniques and the actual damage. With this as a basis, various guidelines for preventive and remedial measures have been proposed with specific reference to the local building methods and typologies.

Keywords: Croatia, war, earthquake, historic buildings, damage, prevention, remedial measures

1. The characteristics of the historic buildings and the surveyed damage

The main walls of the buildings of Dubrovnik and Ston are usually made of sack masonry, with the timber floors and roofs supported by stone cantilevers inserted in the walls (Fig. 1); this structural solution, because of the lack of connection to the walls, does not help develop the co-operation among the walls themselves, which would allow them to resist the horizontal forces more effectively.
In Dubrovnik the signs of shell impacts are still visible on the fronts of the houses: direct hits struck about 70 % of the 824 buildings of the inner city. Further damage was produced by the fires following to the explosions (Fig. 1): the roofs of 5 buildings were affected by fire and in 9 buildings the roofs and floors were completely destroyed.
The damage caused by the earthquake of September 5th 1996 (peak ground acceleration of 0.6 g, epicentre 10 km SE from Ston) can be traced, however, to other causes. These are:

Intrinsic weakness of the sack masonry (weak bond, decay of the mortar):which explains the detachment of blocks in the external skin and the collapse of entire sections of wall. (Fig. 2).
Structural weakness of the walls: in the façades which were almost parallel to the seismic action (left façade in Fig. 3) cracks under the windows, due to the insufficient stiffness of the floor bands (reduced thickness of the zone under the windows, the lack of horizontal ties), were frequently noted; the façades almost perpendicular to the seismic action were often detached due to the inadequate connections to the lateral walls (left façade in Fig. 3).
Lack of connection between roofs and floors with the walls, which not only reduces the co-working of the walls, but sometimes leads to the slippage of the roofs themselves.


Fig. 1


Fig. 2


Fig. 3

2. Preventive and remedial measures

The rigid application of the Croatian Seismic Code regulations would have required the large use of reinforced concrete elements; we succeeded however in following a different philosophy, using where possible, the traditional constructional techniques.

The materials: the intrinsic weakness of the sack masonry construction requires, both as a preventive and a remedial measure, the injection of the walls, or, in the case of very loose material, which was very common, the use of grout percolated in from the top; cracks, depending on their width, could be filled with grout or repaired with the technique of "unpicking and sewing".(toothing out and bonding)

The walls: different measures could be adopted depending on the characteristics of the building.
a) Insertion of horizontal ties at floor level to connect the walls together.
b) Construction of a kind of "kerb" (Fig. 4a), using various possible technical solutions (Fig. 4a', 4a"), at the level of the roof to connect the upper part of the walls (fig. 4b) and to connect the roof to the main walls (Fig. 4c).

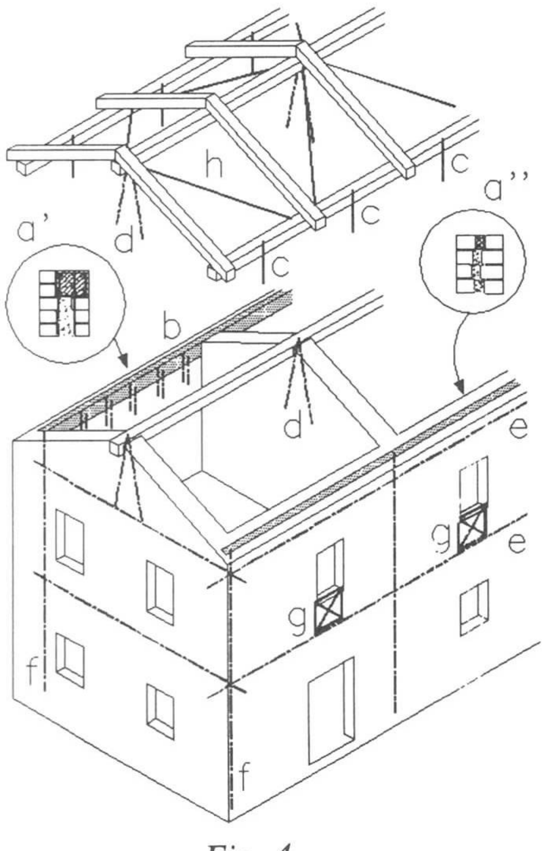

Fig. 4