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A penetration test to evaluate wood decay and its application to the Loggia monument

E. GIURIANI, A. GUBANA

Department of Civil Engineering, University of Brescia, Via Valotti 9, 25133 Brescia, Italy

Facing the problem of restoration and consolidation of wooden beam floors and roofs of historical buildings and ancient masonry houses, it is important to evaluate wood decay in a reliable way. The techniques usually adopted require the taking of samples, laboratory tests, radiographs or ultrasound analysis, while tests in situ *are usually based on yard practice and generally give only some qualitative information about wood condition. In the present work a method and an operative technique are proposed which make penetration measurements possible. The test can be regarded as an extension of the dynamic penetration test used for soil investigation and it is based on the penetration of a graduated rod, which advances by means of repeated blows of a rebound hammer. A preliminary study was done to identify and prepare the most suitable equipment. An attempt to find a possible correlation between wood flexural strength and penetration test results was also done and the correlation curve for spruce wood seems to give a reliable result. This technique was proposed and adopted for a broadbased investigation of the roof vault of the Palazzo della Loggia, a 16th century building in Brescia (Italy), and it gave useful indications of the extent and depth of the decay of the supporting wood structure.*

1. INTRODUCTION

In historical monumental buildings and also in ancient masonry houses, wooden beam floors and roofs often show signs of degradation. In their restoration and structural consolidation the evaluation of decay is important when deciding the possibility of restoration, the kind of repair works needed and the cost.

The usually adopted visual checks can generally give only an idea about the situation and some qualitative information on the external surfaces. Only an extensive withdrawal of samples to test can give reliable knowledge of the situation, but this kind of investigation is onerous and should be limited to a few points in order to avoid excessive damage to structural elements. By this method, specific information and mechanical characteristic measures cannot be directly obtained *in situ*, because the samples must be tested in the laboratory according to standard codes [1]. Furthermore the limited number of samples gives only some local information.

In yard practice, a very simple test frequently adopted is based on the penetration of a nail hit by a hammer without damaging the wood. In reality this test gives only qualitative information about the wood condition. This is the basic idea of the non-destructive test proposed in the present research work, which consists of the penetration of a steel pin into wood with repeated blows transmitted by a rebound hammer. In this way deep wood layers can be reached to obtain information about the interior of beams.

The proposed method can be regarded as an extension of the dynamic penetration test used for soil investigation [2]. An operative technique is proposed which makes penetration resistance measurement possible for layer after layer.

This approach gives more information than that given by the penetration of a semispherically ended rod or steel balls, as specified by the codes [1,3], because these tests only give indications about the superficial layer conditions. Also, the pylodin technique [4,5] gives information about the average strength of superficial layers of about 4 cm depth, but not detailed results. The evaluation of the decay of successive layers of wood is particularly important because the extent of decay can be very different from one layer to the next.

An attempt to correlate the proposed penetration test measures with the mechanical properties of wood is another aim of this paper. As in the soil penetration test, particular attention is devoted to the problem of wood-to-steel-rod friction. In fact the friction of the steel pin may affect the correlation between wood mechanical characteristics and penetration, especially when the rod reaches the deep layers of the wood.

The motivation for this work came about during studies of possible vault restoration for the Palazzo della Loggia in Brescia (Italy), a 16th century building which was designed by the Italian architects Palladio and Sansovino [6] (Figs 1 and 2). The vault is made of a series of truss-type wood arches of considerable dimensions which show evident degradation. The restoration is important for both historical and architectural reasons and depends very much on reliable knowledge of the wood condition. The sampling technique, even if very small cores were taken, would not

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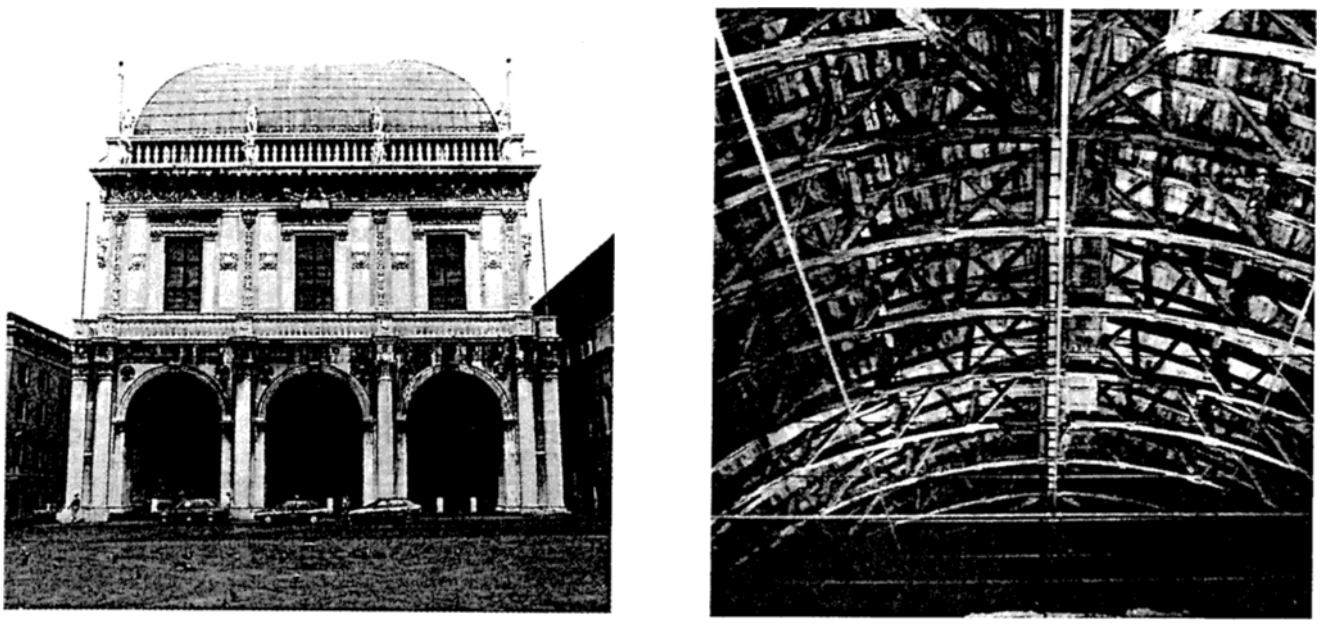

Fig. 1 A view of the Palazzo della Loggia in Brescia (Italy) and an internal view of wood-truss arches.

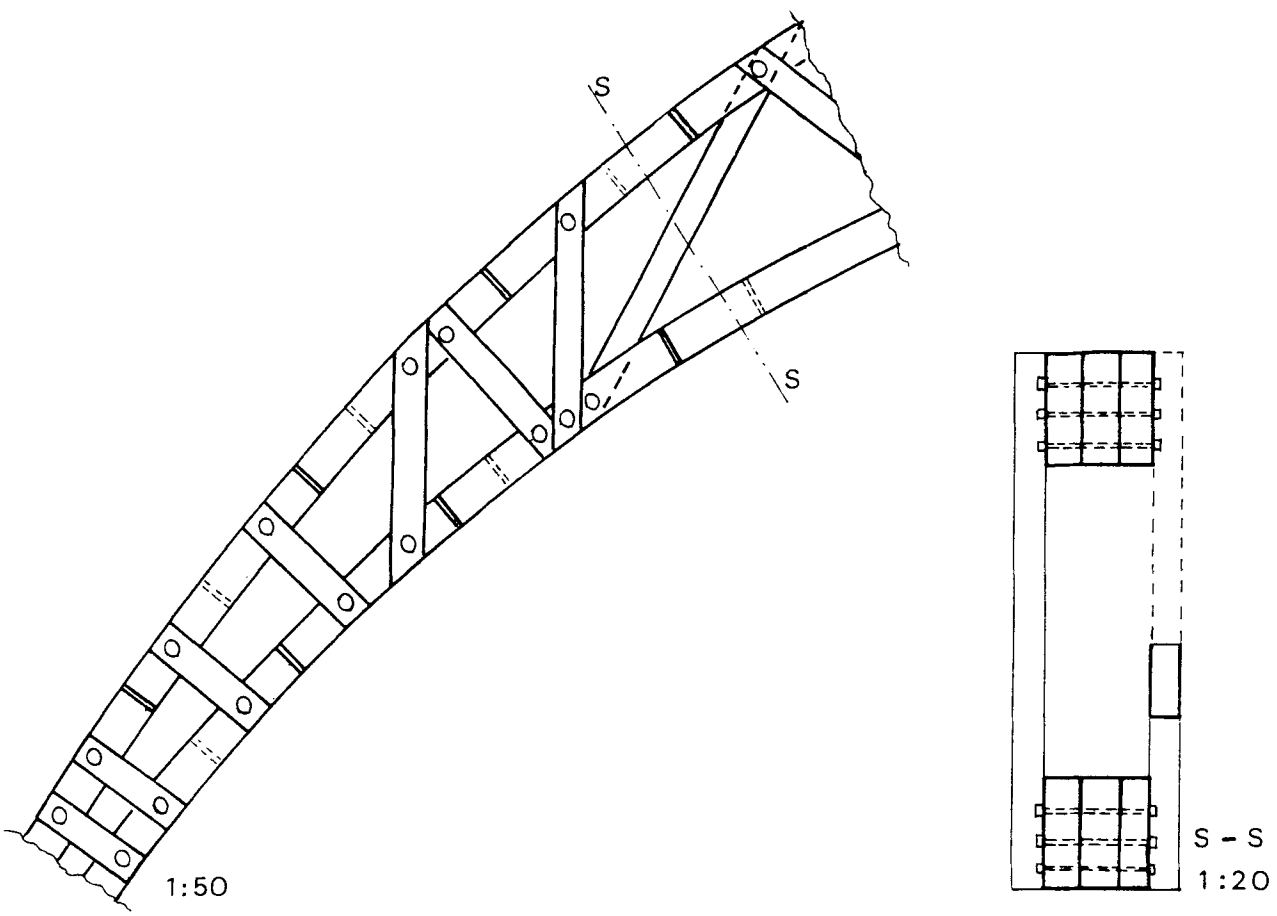

Fig. 2 Enlargement and section of a wood-truss arch.

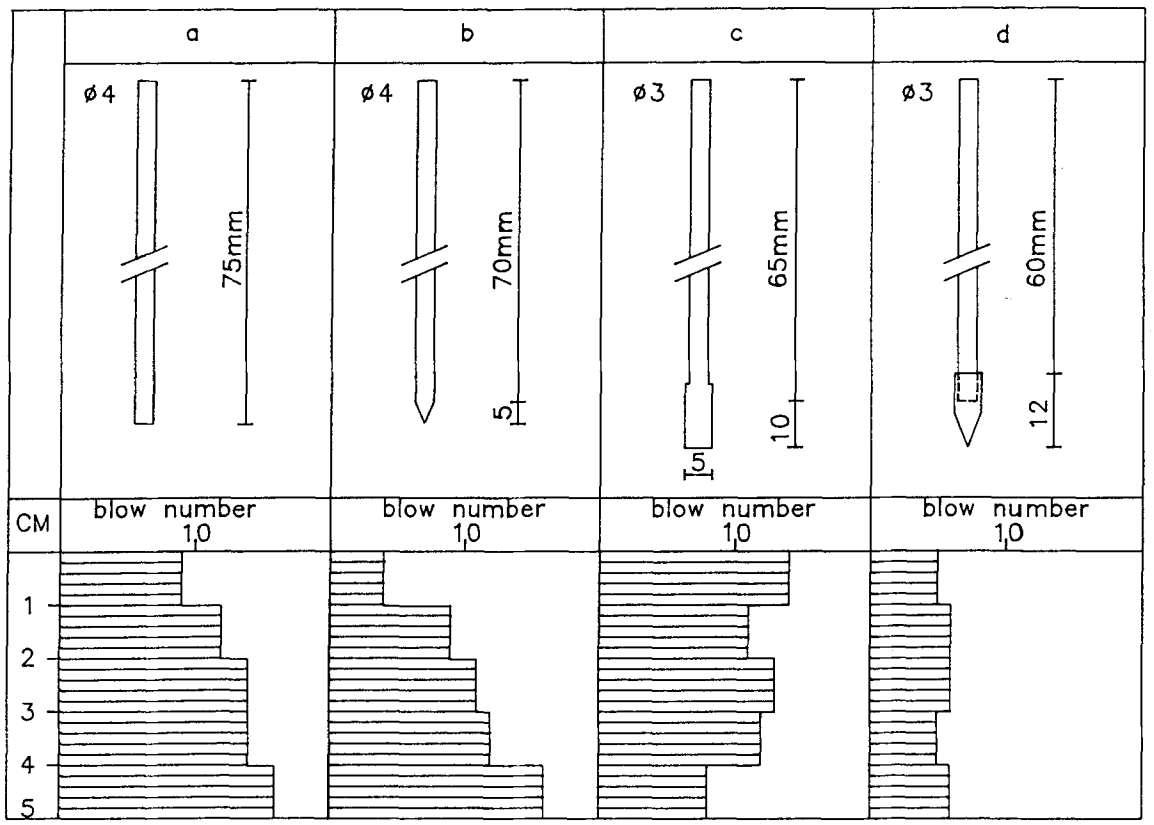

Fig. 3 Different kinds of tip and results of the penetration test.

be feasible for an extensive investigation of the Loggia vault. Only a few samples in the most deteriorated areas were withdrawn because the formation of several holes could have further damaged the wood and compromised the structure's resistance. Furthermore, there were difficulties in placing the core drill machine in many areas because they were not easily accessible.

2. EXPERIMENTAL METHOD AND EQUIPMENT

In the present research work an initial idea, which was easier in practice, was to use a nail pistol to measure a simple blow nail penetration. However, this test was discarded because the information was limited to an average value of the resistance of the different layers crossed by the nail, as in the test proposed previously [4,5].

In fact, the proposed method is based on the penetration of a 3 mm diameter graduated rod, which advances by means of repeated blows of a 2.2 J impact energy rebound hammer commonly used for concrete. This particular rebound hammer proved to be well calibrated and very suitable for this purpose, because it is able to advance the rod about 1 mm per blow in hard wood so that it is possible to investigate deeper layers up to 10 cm with a reasonable number of blows. Preliminary investigations were done to define the shape and proper dimensions of the rod tip to use.

In this study the importance of such phenomena as the wood-to-rod lateral friction, which reduces the blow effectiveness, and the rod instability during penetration were investigated. Furthermore, particular attention was devoted to recovery of the rod so as to avoid permanent test marks. Four different types of tip shape (Fig. 3) were investigated with a view to avoiding lateral friction due to the natural reclosure of wood fibres after the rod penetration.

To evaluate the friction effect several tests were done, first with a constant-diameter rod shank (Fig. 3a and b) and successively with a 25% reduced rod shank diameter (Fig. 3c and d). The flat tip types (Fig. 3a and c) were tested in order to verify whether the punching of wood fibres could deter partial reclosure of the hole around the rod. The diagrams of Fig. 3 give the blow number for a 1 cm penetration of the different rod tips.

Only in case d is friction so imperceptible that it does not influence the blow number during penetration and the behaviour is more regular. For these reasons this kind of tip was adopted for the tests in the Palazzo della Loggia.

To solve the problem of rod extraction after the test, a clutch tip (Fig. 3d and Fig. 4) which can be disconnected

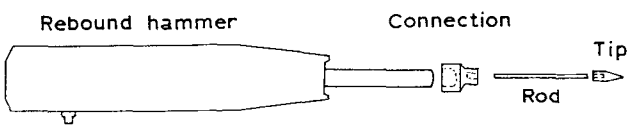

Fig. 4. Equipment used (rebound hammer impact energy 2.2 J).

from the shank was adopted, so that when the penetration test was concluded the rod shank could be easily recovered. In this way no signs of the tests were evident aside from a little hole.

With regard to instability, the 3 mm diameter shank was made of high mechanical characteristic steel to avoid inelastic bending during penetration. It was observed that the flat-tip rods (Fig. 3a and c) were more unstable than the others.

Shanks of different lengths were used; the shortest of 7 cm length made 6–7 cm penetration possible, without instability phenomena during the initial blows. A particular connection between the rod shank and the rebound-hammer plunger (Fig. 4) was studied to avoid bending of the shank under the blow load when it was not coincident with the axis of the rod.

The graduated shanks were progressively substituted by longer ones to continue the penetration from 7 to 14 cm (note that it was not possible to use a 14 cm rod at the beginning of the test, because it was too slender and bent under the blow load).

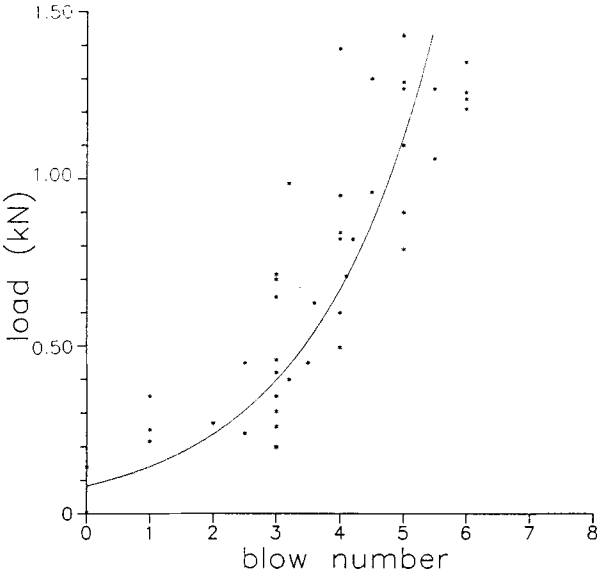

Fig. 5 Correlation between the blow number of penetration test and the standard three-point bending test. Fitted curve $y = 8.41\ e^{0.52x}$ calculated for about 50 experimental data.

3. CORRELATION BETWEEN PENETRATION TEST RESULTS AND A STANDARD WOOD FLEXURAL TEST

The aim of the investigation was essentially to find a possible correlation between the results obtained with the proposed methodology and the wood mechanical characteristics obtained from a usual three-point flexural test. The flexural test was made on a wood prism of 2 cm × 2 cm × 30 cm in accordance with ISO 3133 [1]. Particular care was devoted to sampling pieces of wood with homogeneous characteristics of degradation. After the flexural test the cracked samples were tested with the

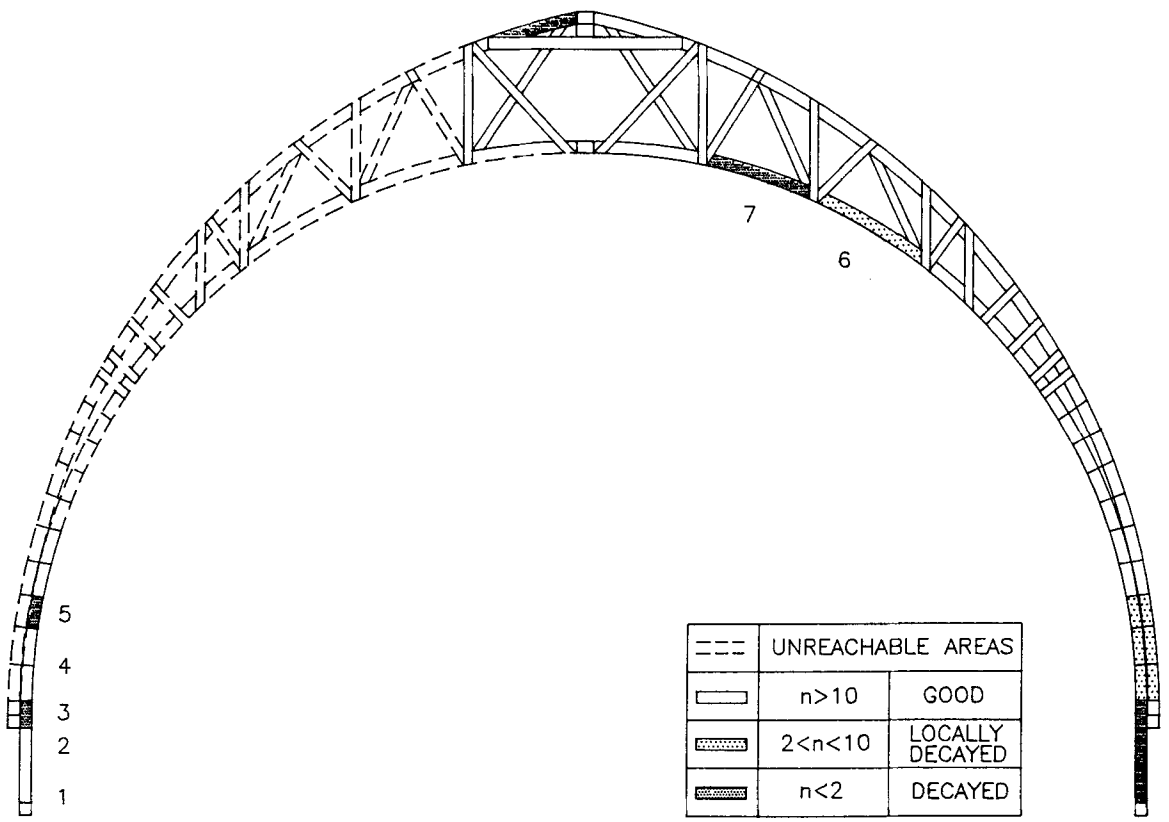

Fig. 6 Arch No. 1 state of degradation.

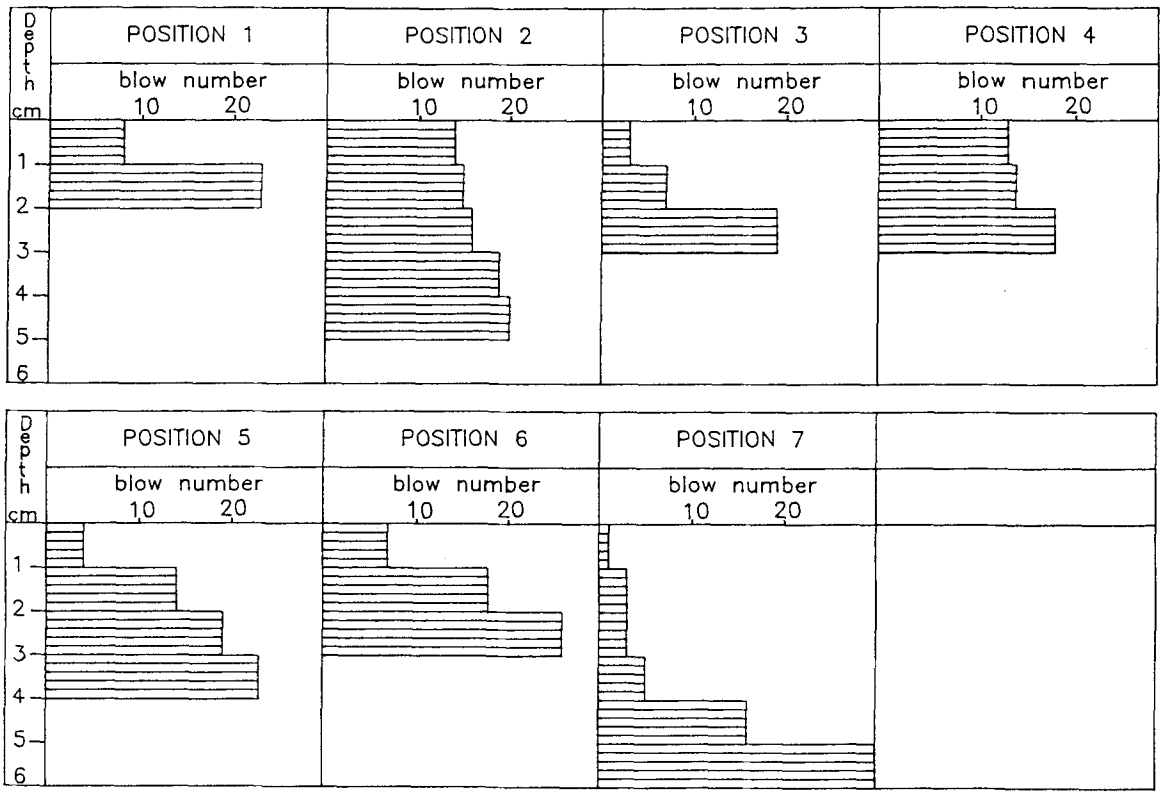

Fig. 7 Penetration test diagrams of arch No. 1.

penetration equipment. For this test the samples were glued with epoxy resin at their bottom face in the middle of the upper face of a 20 cm × 20 cm × 50 cm wood prism.

During the penetration test no wood splitting occurred and no differences between the results for confined and unconfined samples were found. The penetration test was carried out in a transverse direction with respect to the wood fibres and in a radial direction with respect to the annual rings. Owing to the very small transverse size of the samples (20 mm) the rod tip (12 mm) was previously hammered into wood and the blows were counted to penetrate 10 mm.

The wood humidity was controlled and was about 12% in every sample. In Fig. 5 the experimental values of load versus number of blows for 1 cm penetration are plotted for different samples of spruce wood obtained from pieces of different degree of decay. A fitted exponential curve is also plotted, which shows a good correlation between the flexural strength and penetration test results. The experimental points are quite close to the fitted curve.

4. RESULTS OF INVESTIGATION OF THE LOGGIA VAULT

With regard to the investigation of the decayed situation of the oak wood structure of the Palazzo della Loggia, the results are illustrated in Figs 6–9. In Fig. 6 the decayed areas of one particularly significant arch are indicated. Three different indices of degradation were adopted. The first level corresponds to a very decayed situation (the blow number for 1 cm penetration is less than 2), the second indicates a better situation (the blow number for 1 cm penetration is less than 6). No decayed wood required more than 10 blows for every centimetre of penetration.

In Fig. 7 some penetration histograms are drawn. They show that the depth of the decayed areas does not generally exceed 2 cm; only at point 7 does it reach 5 cm.

In Figs 8 and 9 a view of the complete structure is presented, pointing out the decayed areas and the different decay levels measured. In order to not damage the ancient Loggia wood structure very few samples were taken, so that it was not possible to obtain specific correlation curves. On the other hand, the measure of the extent and depth of the decayed areas was the real goal of the Loggia investigation.

5. CONCLUSIONS

The present study to evaluate the degree of decay of a wood structure makes it possible to offer the following comments:

1. The technique of measuring rod penetration caused by repeated blows of a rebound hammer for concrete seems to be effective and reliable for investigating the extent and depth of decay of wood. It is possible in each layer of wood to distinguish different degrees of decay as a function of the number of blows necessary for 1 cm penetration.

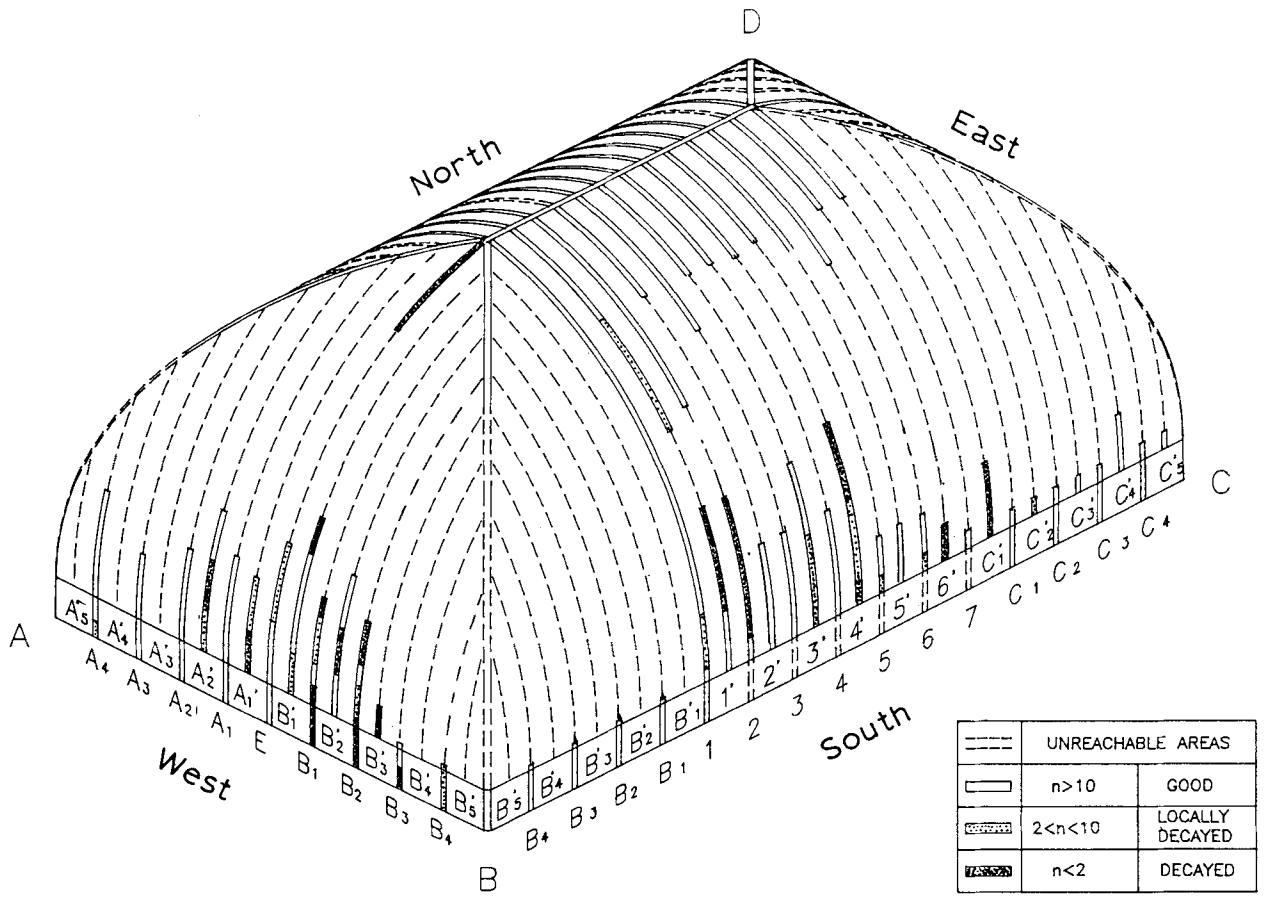

Fig. 8 View from south-west of Loggia vault state of degradation.

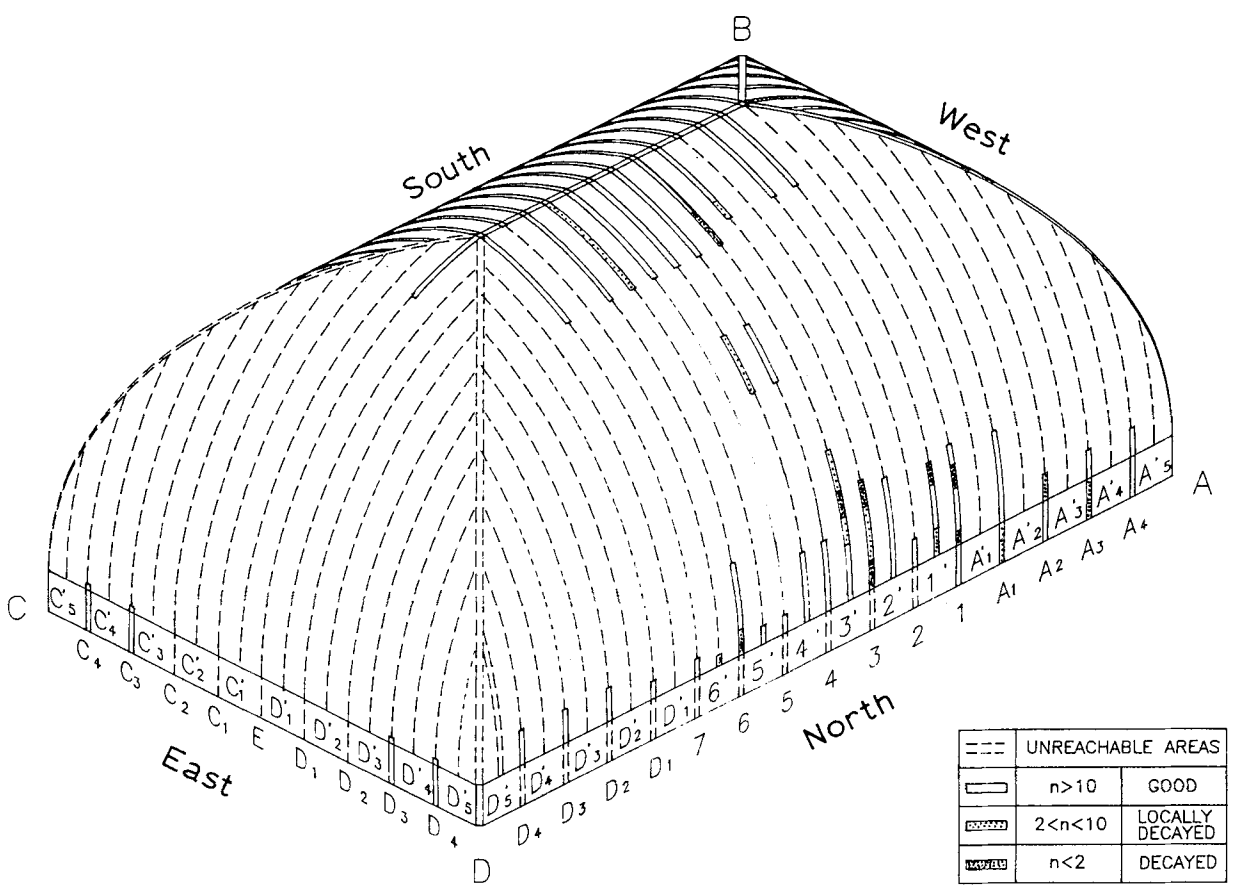

Fig. 9 View from north-east of Loggia vault state of degradation.

2. There is a good indication of the possibility of correlating the flexural resistance of wood with the penetration test results; the correlation curve for spruce wood seems to give a reliable result.

3. The proposed technique was used for a broadbased investigation of the roof vault of the Palazzo della Loggia and gave useful indications about the condition of the supporting wood structure.

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RESUME

Essai de pénétration pour l'évaluation de l'altération du bois. Application aux demeures historiques à loggia

Quand on se trouve confronté aux problèmes de restauration et de consolidation de poutres de bois soutenant les planchers et toitures de monuments historiques et de maisons en maçonnerie ancienne, il convient d'évaluer avec sûreté l'altération du bois. Les techniques dont on se sert habituellement demandent le prélèvement d'échantillons, des essais de laboratoire, une analyse radiographique ou ultrasonique; d'autre part, les essais in situ *s'appuient en général sur une technique de terrain, et fournissent seulement quelques informations qualitatives sur l'état du bois.*

Dans ce travail, on propose une méthode et une technique opératoire qui permettent d'effectuer un essai de pénétration que l'on peut considérer comme une extension de l'essai de pénétration dynamique utilisé pour les études de sol. Le principe de cette technique réside dans la pénétration d'une tige graduée qui avance grâce aux rebonds répétés d'un marteau. On a effectué une étude préliminaire pour trouver et mettre au point l'appareillage le mieux adapté. On s'est également efforcé d'établir une corrélation entre la résistance à la flexion du bois et les résultats de l'essai de pénétration. La courbe de corrélation pour le bois de sapin semble donner un résultat sérieux. Cette technique, proposée et adoptée pour une vaste étude menée sur la voûte en bois du Palazzo della Loggia, un bâtiment du 16ème siècle de Brescia, a fourni des indications utiles sur l'étendue et la profondeur de l'altération de la structure portante en bois.