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On the delamination phenomenon in the repair of timber beams with steel plates

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HIGHLIGHTS

- A non-invasive technique for the repair of ancient wooden floors is presented.
- Steel plated were glued on one side into longitudinal routed grooves.
- The plate delamination was studied with the Moiré interferometry analysis.
- The plastic strain of sapwood markedly reduced the risk of delamination.
- The continuous monitoring of the floor confirms the effectiveness of the technique.

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ABSTRACT

This paper presents a non-invasive technique for the repair of ancient wooden floors. Steel plates are glued on one side only by epoxy-adhesive into longitudinal grooves in order to allow the free swelling and shrinkage of the wood in the direction transversal to the plate glueing surface, thus reducing the risk of plate delamination. A set of high strength steel nails provides load transmission from the steel plates to the wooden beam in the case of loss of adhesion due to fire or delamination. This technique was used to repair a precious beam in a 15th-century wooden floor in Palazzo Calini (Brescia, Italy). The technique requires particular attention because it might be affected by the delamination of the glued reinforcement due to stress concentration, which occurs at the end of the repairing element or at any cracks in the repaired beam. Results of experimental studies on delamination phenomenon investigated by means of the Moiré interferometry analysis are also presented. These show that the risk of plate debonding can be markedly reduced by the capability of the sapwood to develop plastic strain. The wooden floor has been monitored for more than fourteen years, confirming the effectiveness of the adopted technique.

1. Introduction

In the rehabilitation of ancient buildings the problem of strengthening and repairing wooden beams is encountered often. In recent years, theoretical, numerical and experimental studies have been carried out to find valid techniques to enhance the stiffness and the strength of ancient wooden floors. These techniques are essentially based on the use of thin collaborating concrete slab or steel plates [1,2]. Several techniques have been developed since the 1960s, which are especially focused on strengthening and repairing local fractures or defects in wooden beams with steel plates bonded by epoxy adhesive [3–6]. More recently, fibre-reinforced polymer (FRP) sheets have been proposed to replace steel plates because they are easily installed and provide good durability [7–11]. Generally these techniques require wide steel plates or FRP strips which cover a large part of the surface of the wooden beam. This aspect makes it difficult to apply these techniques to the repair of precious ancient wooden floors.

The restoration technique proposed by Gentile et al. [12], Alhayek and Secova [13] and by Alam et al. [14] seems to be more acceptable. It uses glass-fibre (GFRP) or carbon-fibre reinforced polymer (CFRP) reinforcements that were glued into narrow longitudinal grooves routed out of the wood beam. This limits the intervention to a reduced portion of the beam, which remains mostly visible. This technique was adopted to efficiently strengthen 75 timber beams of a bridge in Canada [12]. All of the previously mentioned techniques, based on the collaboration between two elements of different materials, pose the issue of stresses occurring between the reinforcing element and the wood, induced by the

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wood's swelling and shrinkage resulting from its cyclic changes in moisture content.

Another important issue raised by these reinforcing techniques concerns the risk of delamination, as the collaboration between the two materials – steel and timber – results in a concentration of normal and shear stresses induced by a discontinuity of one of the two elements (Fig. 1). Two brittle failure modes characterise the debonding from timber of adhesively-bonded plates: delamination might occur (i) at the cut-off point of the plate, propagating inward along the beam (end peeling) or (ii) at the toe of transversal fractures of the repaired beam and it moves toward the plate ends (midspan debonding) (Fig. 2). In recent years, these phenomena have been widely studied but specifically for reinforced concrete beams strengthened with steel plates [15,16] or with plastic reinforcements (FRP) [17,18]. These experimental studies showed that the strength and the stiffness of the beam can be substantially increased with the modulus and the amount of the applied reinforcements. However, the effectiveness of the technique may be impaired by plate delamination, which mainly depends on the characteristics of the concrete cover, shear span of the beam and on the extension of the bonded plates. Moreover, the research studies of Rahimi and Hutchinson [17] and of Sebastian [18] pointed out that the use of thin plates may encourage midspan debonding rather than end peel action in a plated beam.

Several numerical [19,20] and analytical [20–22] research studies were also carried out. Although all these theoretical studies have shed light on interface stress concentrations, they do not interpret real local diffusive effects because they assume a linear elastic behaviour of the connected materials. It should be noted that few numerical studies take into account non-linear constitutive relationships for the plate-concrete bonding interface to model concrete beams strengthened with bonded FRP reinforcement [23,24], thus allowing for a mitigation of the stress concentration. Despite the several experimental studies which show the effectiveness of steel or CFRP reinforcement to strengthen [12,13] or repair fractured timber beams [15], few specific investigations aimed at studying the delamination phenomenon are available in the literature [4,5].

In this paper a repair technique adopting steel reinforcing elements glued into grooves is presented with particular devices to avoid both the risk of the interface splitting due to the wood swelling and shrinkage, and the risk of collapse due to the delamination of the repairing element induced by peak stress. This technique was used to repair an ancient beam in a 15th-century wooden floor in Palazzo Calini (Brescia) which has also been monitored for more than fourteen years since the repair. Results of experimental studies focusing on the delamination induced by stress concentrations and investigated by means of the Moiré interferometry analysis are also presented. This experimental campaign was carried out with the specific aim of understanding the role of the local shear behaviour of sapwood in the onset of plate debonding.

2. Degradation assessment of a fifteenth-century beam

The repair was carried out on a larch main beam of a fifteenth-century wooden floor in "Palazzo Calini ai Fiumi" (Brescia, Italy). The beam is 220 mm wide, 500 mm deep with a 7.5 m clear span. The distance between the main floor beam centres varies between 3.2 and 3.7 m. These support the secondary beams (110 mm wide and 150 mm deep) with a spacing of about 0.55 m (Fig. 3). It should be noted that the beams of Palazzo Calini are covered by an ancient and precious paint, which does not allow a clearly defined classification of the timber as it may be done for new elements. However, on the basis of a visual grading of the dimension of main knots, the characteristic bending strength should be about 20 MPa as suggested by Italian standard for larch [25].

On 1997 the floor was stiffened by replacing the original lime-mortar slab with a 50 mm thick collaborating concrete slab

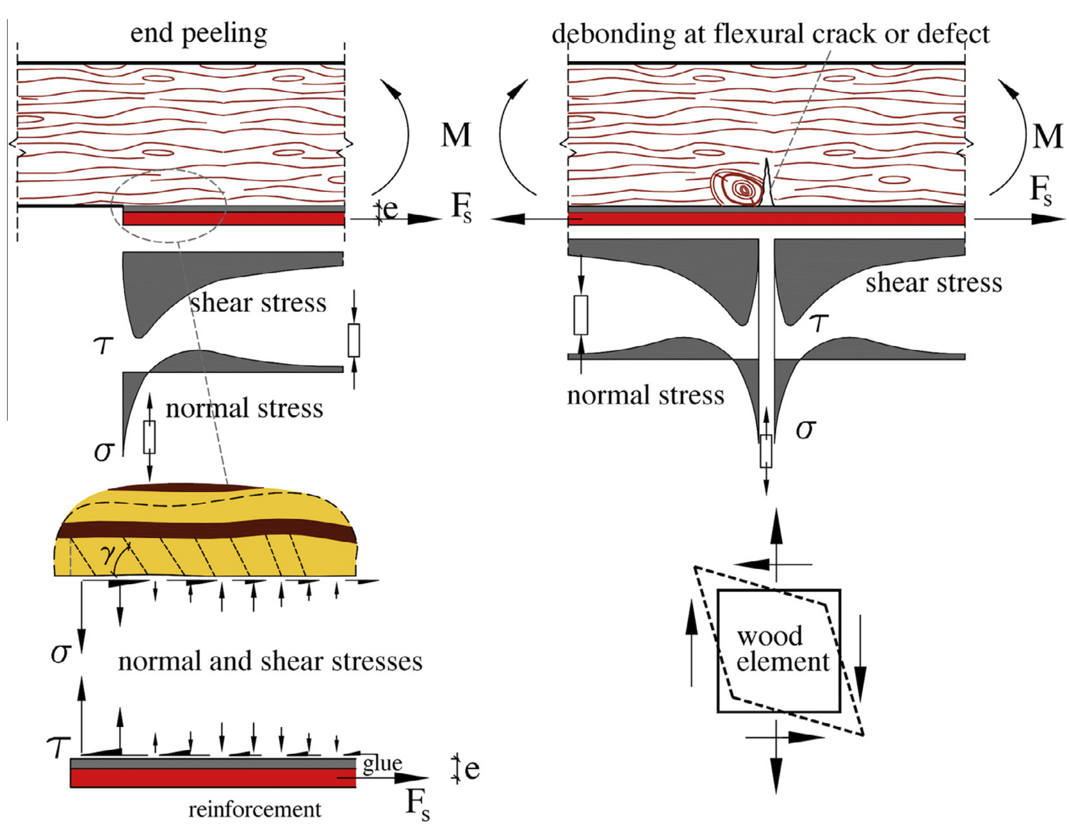

Fig. 1. Stress concentration at plate ends or close to beam defects.