"LCC analysis for glued laminated timber components exposed in external"

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Topic: *Life Cycle Management*

Abstract

The aim of the experimentation is to characterize the performances of glued laminated timber components exposed to atmospheric agents, in the light of the concept of Life Cycle Cost, particularly emphasized in the Italian new legislation on public works.
In fact, it could be seen that the design of the construction details and the initial characteristics of glue laminated timber components, require a particular attention to avoid errors that may undermine the possibility to perform the structural functions for which, above all, this material it is dedicated.
The experimentation consisted of a series of tests aimed to identify the performance of glued laminated timber beams taken in site, after a work executed some years ago on a theatre built in Roman era, and to compare them with similarly manufactured new elements. The tests performed were thermography, ultrasound, Wood-Pecker penetrometer, mechanical characterization.
The results will be used to begin setting limits and conditions for outdoor use of glue laminated timber, and assume a reliable life cycle, and consequently identify the most appropriate maintenance strategy for the LCC.

1. Introduction

The design of new building products, as well as that of interventions on existing buildings, can represent an opportunity for adopting good building materials and systems to increase sustainability. This is the case, for example, of structural elements in glued laminated timber, which are often preferred to reinforced concrete and steel, especially for the realization of exposed components.

Glued laminated timber is, as known, a composite material, essentially made of natural wooden layers glued with specific resins, and made on an industrial scale. In addition, the outer surface of the elements is generally treated by applying resins or special paints with the aim of protecting them from atmospheric agents and biological attacks. However, it is frequently observed that such protective capacity, especially under certain conditions of exposure, is not sufficient to preserve the physical and mechanical characteristics of the element over time, despite the assurances of the manufacturers in this regard.

This results in the need to evaluate design choices, regardless of the Life Cycle Cost Analysis, which is particularly emphasized in current legislation on public works (Leg. Dec. 50/2016). It is worth recalling that this Decree, in relation to the award criteria (art. 95-96), introduces the cost element, following a cost/effectiveness comparison criterion, which really includes the Life Cycle Cost Analysis, in addition to the Life Cycle Assessment.

In the light of the LCC applied to glued laminated timber, it is obvious that it is fundamental to consider the parameters that influence its evaluation, such as the specific technical solution adopted and the way in which it is installed. This is to adequately consider the effects of exposure to atmospheric agents. Consequently, the design choices regarding the characteristics of the glued laminated timber that is adopted and the constructive details to realize, can have a decisive influence on LCC.

With the ultimate goal of evaluating the LCC, the experimentation in question consisted in the performance characterization of glued laminated timber beams (taken in a historic site, an ancient Roman theater) by performing a series of laboratory tests such as thermography, ultrasound, Wood-Pecker penetrometer, compressive test. At the same time, a similar performance characterization has been performed on newly manufactured laminated wood elements with identical features to those of the elements investigated at the time of installation.

2. Materials and methods

2.1 Characteristics of materials

In order to determine the variation in the performance characteristics of glued laminated timber elements due to exposure to atmospheric agents, an experiment that compared two sets of glued laminated wood beams was carried out in the laboratories of Tecnolab s.r.l. in Naples, the first one taken from an ancient Roman theater, set up around 15 years ago to allow the walk on 3 moats, and remained naturally subjected to atmospheric agents, the second one of new supply.

The beams have a rectangular cross section of 24 x 14 cm, and consist of 6 glued layers 4 cm each. Observing the conditions of laying of the aged elements, two different situations were found corresponding to the same pattern of laying, different for the framework of the elements. In the first case (“A” configuration, fig.1), the elements, approximately 200 cm long, are positioned in the direction of development of the moat, and are supported on transversal profiles of HEA galvanized steel, in turn supported to cover the clear span. In the second case (“B” configuration, fig.2), glued laminated timber beams are directly supported on the stone elements that form the edge of the moat.

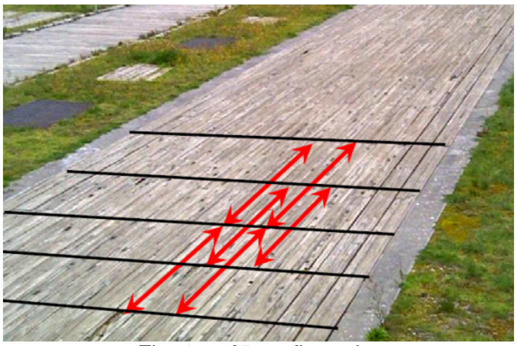

Fig. 1 – “A” configuration

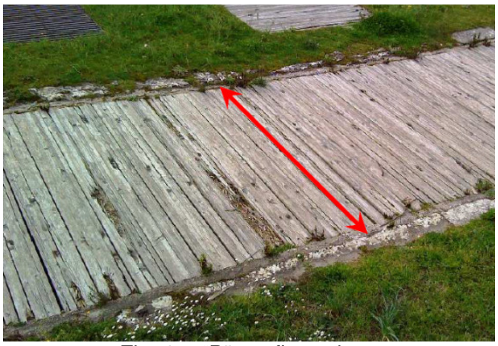

Fig. 2 – “B” configuration

From a technological point of view, in both cases the laying condition showed, first of all, a limit that was due to insufficient attention to the design of the constructive detail. In fact, while in the first case the support of the wooden beams on the steel profiles is made up of an insufficient support area (Fig. 3), in the second case, although the supporting area is sufficient, the wooden elements are directly in contact with the tuff-shaped stone ones, forming the edge of the moat. This creates a condition that inevitably - given the exposure to the atmospheric agents and also the propensity of the tuff to retain water - leads to a progressive deterioration of the beam headpieces, which basically are always in very high humidity conditions (Fig. 4).

Fig. 3 – Bearing on steel profiles (“A”)

Fig. 4 – Bearing on stone elements (“B”)

In addition, it is necessary to point out a further anomaly in both cases, that is the orientation chosen for the positioning of the elements: in fact, it is parallel to the layers, unlike the natural layout of these elements, which would clearly recommend a laying with vertical axis orthogonal to the layers.
In this way, the incorrect positioning on the one hand does not allow the glued laminates timber elements to express all the potential mechanical performances, on the other it abnormally exposes the beams to the action of the atmospheric agents, since all the glued surfaces are orthogonal to the meteoric waters coming in zenital direction. The observation of the beams in site highlights the presence of a strong degradation of the elements, more accentuated on the most exposed surface. It follows that the material, although treated on the surface with protective paint, shows a limited aptitude for direct exposure to atmospheric agents. (Figures 6 and 7).
In order to carry out the tests on the material in accordance with the reference standards, 12 parallelepipedic 24 x 24 x 12 cm elements, or beam trunks of 24 cm length, for both types of specimens (see fig. 5, with stress directions highlighted) were prepared.

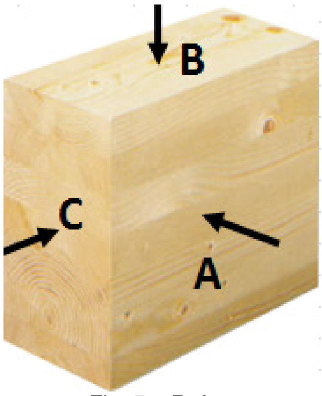

Fig. 5 – Reference sample


Fig. 6 – Degradation in a cross section


Fig. 7 – Degradation of the beam on bearing


Fig. 8 – New wooden samples

2.2 Testing methodology

In order to characterize the performance of glued laminated timber beams taken in site and those of new manufacture, some laboratory tests have been carried out in Tecnolab srl. The tests carried out were non-destructive (thermography, ultrasound), partially destructive (penetrometer Wood-Pecker), and destructive (compression test).
Except for the thermographic survey, the tests were carried out on both types of glued laminated timber elements and then compared.
The choice of performing ultrasonic and penetrometric tests has, however, allowed to verify whether the SONREB Method, generally used to determine the mechanical characteristics of concrete elements, may be valid even if applied to glued laminated timber.
The penetrometer used, called "Wood-Pecker", is in fact a N-type sclerometer (for concrete) which is added to a percussion rod with a steel cuff capable of supporting a stud consisting of a hardened rectified steel rod (60 Rockwell hardness) with a circular cross-section of 2.5 mm in diameter, 50 mm overall length (escaping from the headset 44 mm), with a truncated cone tip at an angle of 35°. The steel headset is easily removable from the percussion rod to allow the hammer to be checked for calibration (the manufacturer prescribes that the average of ten sclerometric measures to the anvil must be = 80 ± 2). The tip penetrates into the wooden body following a predetermined number of shots (five to be performed in a consequential manner) and stays there when Wood-Pecker is recovered.

2.3 Structural considerations

The beams subjected to experiments have, as anticipated, 24 x 12 cm section. And the clear span is about 2.00 m. As well known, the most significant stresses, and for which the structure crisis may turn up, are the bending moment in the middle and the shear in the bearings.
By neglecting the mass of the beam and considering an accidental overload of 4 kN/mq:
M = 2.00 kNm/ml → 0.50 kNm/beam;
T = 4.00 kN/ml → 1.00 kN/beam.
In the graph of Figure 9, the diagrams and the values of the stresses related to one meter are represented, to which corresponds a maximum normal tension in the middle of 5.47 N/mmq and a maximum shearing tension of about 0.45 N/mmq (in the graph the values for one meter).
These values are about 10 times smaller than those that represent the characteristic values for the glued laminates timber used.
The characteristic values are of course referred to new wood, but what happens over time? Declared resistance persists under environmental stresses? Obviously no, but it is possible to find parameters to understand when the degradation has reached such a level that the structure no longer guarantees the expected performances with a sufficient safety factor.

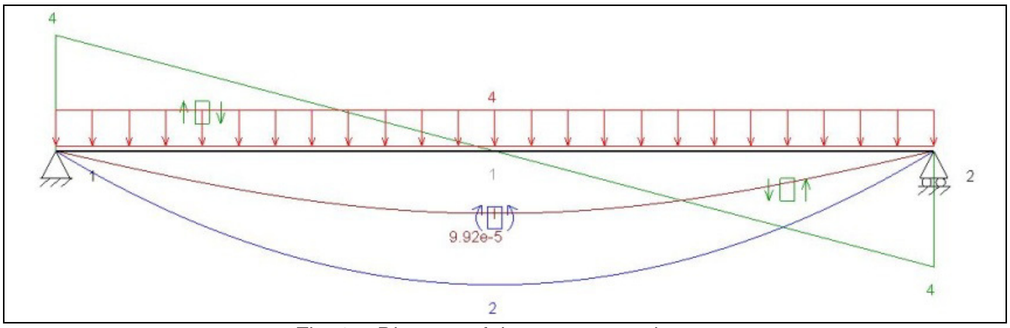

Fig. 9 – Diagram of the stresses on beams

The characteristic to be considered as a parameter is the shearing and bending strength with a safety factor equal to at least 3; that is, the calculation tension remains in any case 5.47 N/mmq per bending and 0.45 N/mmq per shearing; the tension for a wood with a GL 32 profile has resistance values of 36 N/mmq per bending and 4.3 N/mmq per shearing, 31 N/mmq for along fiber compression and 3.6 for fiber orthogonal compression. It is clear that the ratio to the operating values is 6.5 and 9.5 respectively by bending and shearing.
For the purposes of this experiment, it is particularly important to verify whether more or less destructive tests can be carried out to determine when this resistance reserve falls below the acceptable threshold of 3.

2.4 Testing program

As anticipated, for the purpose of the experimentation, the performance decay of glued laminates timber has been analyzed by the effect of aging due to direct exposure to atmospheric agents, by means of the following tests:
Non destructive tests
Thermographic test; Ultrasonic Test (UNI EN 12504-4) with direct measurement method; Penetrometric test Wood-Pecker (UNI EN 408: 1997) for the determination of the penetrometric index; Ultrasonic-penetrometric test (Sonreb) for determination of compression strength.
Destructive tests
Crushing tests for determination of compression strength.

3. Results

3.1 Wood-Pecker penetrometer test

The tests on side B, turned out that unlike side A, the results obtained are much more reliable, except for a few single values, this is even more evident if the trend line is observed. By comparing the trend line referred to the side B and the tendency line referred to breaking, then it is noticeable that they are almost parallel, the error is fairly regular and about 23%.

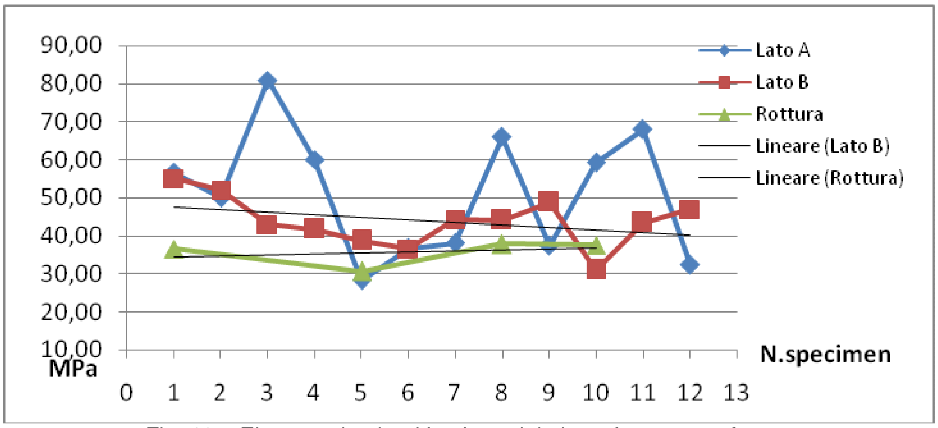

Fig. 10 – Elements in glued laminated timber of new manufacture

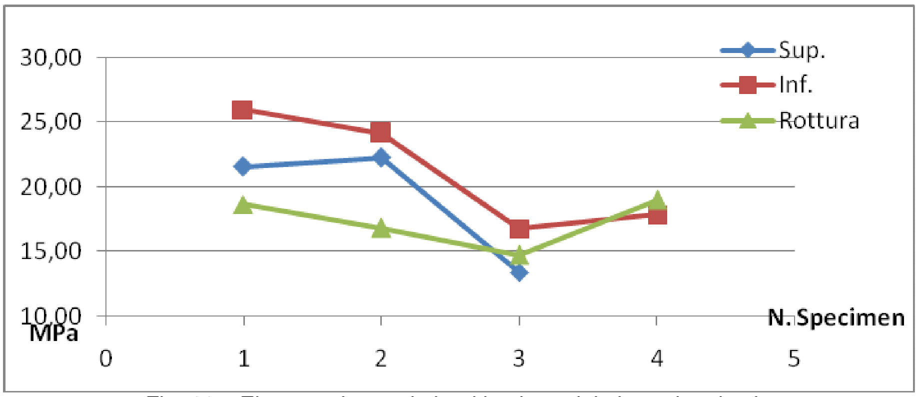

Fig. 11 – Elements in aged glued laminated timber taken in site

By doing the same procedure even on the wooden elements taken in site, an error of about 26% is calculated.

Since the error margin is almost similar, it is also noticed that Wood-Pecker is also consistent, if subjected to a proper initial calibration. Moreover, the results obtained by Wood-Pecker and those referred to breaking are equivalent, which means that the test is reliable, both for wood picked on site and for newly manufactured wood.

From the comparison of the outcomes of the above mentioned tests results a 50% reduction in the compressive strength relative to the two conditions. This corresponds to a 50% increase in the piling value of the peek master in aged beam.

3.2 Ultrasonic test

Analyzing the ultrasound test, executed not in line with the fibers but across (at a distance of 12 cm), the resulting speed is very indicative to see if there is any degradation: where the speed is reduced, it is a symptom of degradation, and also if it is not possible to know the typology, it is possible to know that there is a reduction in mechanical strength. With this single test it is impossible to quantify mechanical strength, so it is rather useless to run it alone, but it is fair to note that the reduction in ultrasonic speed corresponds to a physical degradation of the material.

Ultrasonic testing was carried out along the layers by adopting a distance of 10 and 20 cm and at the side of the fibers at a distance of 12 cm (related ultrasonic speeds are respectively called V10, V20, V12).

By averaging the resistance obtained by considering the three different ultrasonic velocities corresponding to the three different distances used, and comparing these averages with the mean crushing value, it is possible to note that the closest value to the latter, and the most reliable is that relative to V20, both old and new wood.

										Ultrasonic speed						STRENGHT			
SPECIMEN		Test effected	WOODPEEKER					Pm	Pc	V10 ind		V20 ind		V dir		R V10	R V20	R V12	
			Penetration [mm]					medium	medium	d [cm]	m/sec	d [cm]	m/sec	d [cm]	m/sec	[Mpa]	[Mpa]	[Mpa]	
Tr. Centr.	3	C	23,55	22,80	18,80	23,30	26,85	**23,06**	**17,88**	10	3289	20	4034	12		18,66	18,66		18,66
Tr. Centr.	3	C	23,73	19,79	20,71	21,58	20,20	**21,20**	**16,84**	10	3125	20	3571	12		18,66	18,66		18,66
Tr. Centr.	4	C	21,75	21,80	20,10	26,70	23,40	**22,75**	**17,71**	10	3289	20	3571	12		16,84	16,84		16,84
Tr. Centr.	4	C	23,18	19,65	22,60	22,25	21,95	**21,93**	**17,24**	10	3906	20	3846	12		1,55	19,15		16,84
Tr. Lat.	8	C	29,77	29,82	26,88	28,77	27,78	**28,60**	**21,19**	10	2976	20	3206	12		370,76	10,50		14,77
Tr. Lat.	8	C	27,58	25,66	24,57	25,72	25,74	**25,85**	**19,50**	10	4310	20	4237	12		1,66	16,45		14,77
Tr. Lat.	10	C	28,83	25,94	30,79	26,90	27,92	**28,08**	**20,85**	10	3240	20	2970	12		110,71	10,04		19,00
Tr. Lat.	10	C	26,80	24,35	23,14	24,65	26,74	**25,14**	**19,08**	10	4143	20	4028	12		2,15	16,34		19,00
								24,58	**18,79**				**Medium Tr. Centr.**			**13,93**	**18,33**		**17,32**
													Medium Tr. Lat.			**121,32**	**13,33**		

Fig. 13 – Ultrasonic test results

The presence of knots or material irregularities greatly influences the outcome of the test, so it is crucial that the operator carefully selects, through direct observation, the area to be tested to obtain reliable values.

It should be emphasized that the test on new wood is more reliable than that carried out on the degraded beams, due to the excessive cracking of the latter which necessarily limited the areas where testing could be carried out.

Through the analysis of the results of the only ultrasound tests, and about the comparison of the two different types of beam, a decay of the compressive strength value exceeded a few points over 50% has been observed.

<u>3.3 Sonreb test</u>

By means of the Sonreb method, it has been observed that for the beams is taken in site the reliability on average remains, while considering the punctual values there are high differences, so that errors occur ranging from 7 % to about 40%. As far as new wood is concerned, the reliability of the results remains and indeed improves with respect to the case of degraded wood. Considering, for example, the resistances calculated with V20 on the side A of the sample, it is possible to note that the margin of error varies from 1% to 10%, which indicates a high reliability of the test performed.

Therefore the correct choice of a test execution procedure, which involves a large number of non-destructive tests on the material, is crucial, as it can happen that the results taken individually are not useful, but on average they become very reliable.

SPECIMEN		Test effected	WOODPEEKER Penetration [mm]					Pm medium	Pc medium	Ultrasonic speed V10 ind d [cm]	V10 ind m/sec	V20 ind d [cm]	V20 ind m/sec	V dir d [cm]	V dir m/sec	STRENGHT R V10 [Mpa]	R V20 [Mpa]	R V12 [Mpa]	
A side	1	C	14,83	16,74	14,06	14,03	14,96	**14,92**	**13,17**	10	3125	20	4386	12	1359	36,50	36,50	36,97	
A side	2	C	15,79	17,52	13,94	16,16	15,41	**15,76**	**13,69**	10	3049	20	4386	12	1515	38,76	37,15	26,49	
A side	3	C	12,49	12,06	10,68	14,38	13,84	**12,69**	**11,71**	10	3472	20	4033	12	1387	28,89	23,82	39,56	
A side	4	C	13,64	15,32	14,59	14,74	14,27	**14,51**	**12,91**	10	3379	20	4386	12	1373	31,63	36,18	36,68	
A side	5	C	19,92	22,29	21,33	19,49	19,02	**20,41**	**16,39**	10	3571	20	4166	12	1390	32,05	32,05	27,58	
A side	6	C	16,89	19,91	17,32	18,84	17,67	**18,13**	**15,09**	10	3472	20	4098	12	1409	32,40	28,69	29,01	
A side	7	C	15,80	18,97	16,64	18,04	19,78	**17,85**	**14,92**	10	3205	20	4033	12	1339	36,99	26,58	33,68	
A side	8	C	14,53	13,80	14,45	13,59	13,24	**13,92**	**12,53**	10	3125	20	4386	12	1305	35,69	35,69	43,37	
A side	9	C	14,80	18,68	17,42	19,52	19,46	**17,98**	**15,00**	10	3289	20	4545	12	1403	35,47	45,39	29,53	
A side	10	C	11,41	15,05	15,15	15,41	15,98	**14,60**	**12,96**	10	2907	20	4386	12	1413	41,05	36,25	33,84	
A side	11	C	12,28	12,95	14,41	15,06	13,93	**13,73**	**12,40**	10	2976	20	3731	12	1437	38,64	17,28	33,90	
A side	12	C	17,72	19,62	20,37	19,65	18,76	**19,22**	**15,72**	10	3049	20	4032	12	1448	41,26	27,18	25,84	
								16,14	**13,87**				**media 1 - 5 - 8 - 10**			**36,32**	**35,12**	**35,44**	**35,66**
															media tot	**35,78**	**31,90**	**33,04**	

Fig. 14 – Sonreb test results

<u>*3.4 Compressive test*</u>

The compressive test allowed to define the wood Resistance Class according to UNI EN 14080: 2013 code. The results obtained show the following characteristics:
New wood: ρ = 472.39 kg/mc> 440 kg/mc; R = 35.6 MPa> 32 MPa (GL32h res class).
Old wood: ρ = 475.92 kg/mc> 440 kg/mc (the specific weight is increased because the wood is impregnated with water)
R = 17.32 MPa <20MPa (the resistance is halved compared to the new wood); this results in the resistance class GL20h.

4. Discussions and conclusions

Experimentation on the case study showed a decrease in the mechanical strength of the beams of 100% in about 15 years of weather exposure, neglecting the punctual problems due to the modalities and conditions of the bearings.
In terms of LCC analysis, this data is useful but inadequate, since it is necessary to evaluate what is the law of performance decay that governs the main characteristic of beams in time (mechanical strength) in order to evaluate, in a corresponding manner, what can be the possible maintenance actions and consequently the most appropriate management strategies.
The case study has highlighted how, at present, it is necessary to fully replace the beams, given the extent and intensity of performance decay, which led them to the end of their life cycle (can be estimated, under this specific conditions, about 10 years).
It is evident, however, that it is possible to prolong this life cycle through various types of maintenance actions, with consequent economic scenarios of different magnitude.

In order to individuate phases and activities in the performance assessment protocol, the sequential procedure suggested in code ISO 15686-7 has been followed, though revised and corrected according to the specific conditions of the case. In the examination phase, the in-use condition was classified in according with the ISO 15686-7 Annex B: so, the definitions of the performance degree were the ones reported in the table below:

DEGREE	TYPE OF SYMPTOMS	IN-USE CONDITION FOR THE GLUED LAMINATED TIMBER BEAMS
1	no symptoms	no performance decay
2	slight symptoms	incipient exfoliations of the protective paint
3	medium	accentuated exfoliations to less than 30% of the surface
4	strong symptoms	accentuated exfoliations to more than 30% of the surface
5	totally unacceptable	partial/total collapse

It is possible to associate a typology of maintenance intervention to each of the listed performances, and to identify the time threshold at which the performance level is reached. In fact, biunivocal bonds exist between each of these three terms (Fig. 13):

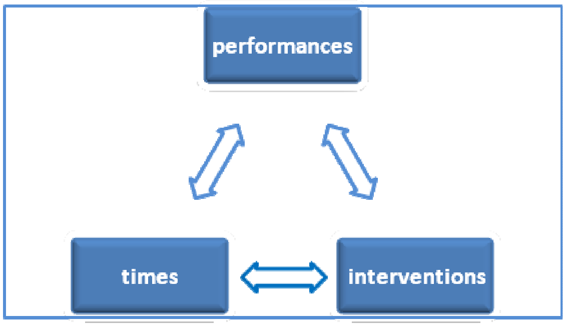

Fig. 15 – Links P/T/I

So, it is possible to associate a typology of intervention to each of the decay levels (in-use conditions, to each of which different performance degrees correspond) listed in table above, according to the following table of correspondences:

IN-USE CONDITION FOR THE GLUED LAMINATED TIMBER BEAMS	MAINTENANCE INTERVENTIONS
no performance decay	None
incipient exfoliations of the protective paint	Partial painting
accentuated exfoliations to more than 30% of the surface	Total painting
accentuated exfoliations to more than 30% of the surface; incipient detachment of the layers; partial rotting	Partial substitution + glueing + total painting
partial/total collapse	Total substitution

However, the experimentation has also demonstrated the possibility to carry out an on-condition maintenance strategy, given the reliability of tests that are little or non destructive. In this sense, a planning of periodic controls can be assumed, by which will eventually result the decision to perform one of the 4 types of maintenance action above highlighted.
The economical parameter deserves a stand-alone mention, both because it is more objective, and because it represents a consistent reason behind this kind of choices.
By executing different typologies of maintenance interventions in a given period of time (that is to do a LCC analysis), as a consequence of maintenance strategies, it is possible to compare the consequences on the expense in the mid-long period, overlooking – of course – other factors, despite having influence, as they would require a multicriteria analysis to be taken into account.
Without a multicriteria approach, in fact, this kind of analysis generally leads to the conclusion that the best strategy is to consume initial performance over the life cycle without any maintenance action, which is true only from the strictly economic point of view, not, as you know, considering other parameters.

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