Composite materials for strengthening of load-bearing wooden structures in historical buildings

Nickolay Linkov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia
E-Mail: nicklinkov@gmail.com

Abstract. The results of tests of a composite material made on the basis of glass cloth and an epoxy binder in the form of ED-20 resin are considered in the article. The main strength and elastic characteristics of the composite are obtained experimentally, including taking into account the set of strength of the epoxy matrix in time. It is shown that for the proposed composite material, a set of strengths for all main types of stress state up to the level of 70% of the calculated value occurs on average for 16 days, to a level of 90% of the calculated one for 45 days, 95% of the calculated value for 60 days from the beginning Curing the composite on the surface of the structure. Statistical analysis of the strength and deformability parameters of the composite material, comparison of the strength of the composite material and wood at different reliability levels for the main types of stressed state of wooden elements in building structures are given. The results of numerical strength analysis in the ABAQUS program complex of the state of stress of a compound at different thicknesses of a composite material are presented.

1. Introduction
Wood is a natural building material that occurs in old structural wooden structures of historic buildings, where the structures are made of massive wooden elements that have not undergone modern machining. Uneven surface of wooden structures, characteristic for roughly processed timber, makes it difficult to restore and strengthen wooden elements with modern tape and sheet composites. For these cases, it is necessary to form a composite material directly on the surface of the elements to be reconstructed. At the same time, a composite material and adhesion bonds between the composite and the surface of the wooden elements are simultaneously formed. If the properties of industrial composites are ensured by the quality of the raw materials, the quality of production, are controlled in the factory laboratories and are guaranteed by the manufacturers, the properties of the composite materials and compounds formed on the site and directly on the construction require careful study.

2. Literature review
For today, the connections of wooden structures continue to remain an actual direction for diverse scientific researches [1, 2, 3, 7]. The author of the article also has experience in studying the stress-strain state of joints of wooden structures [4, 5, 6, 8, 9]. The analysis of the international experience on strengthening joints of wooden elements with composite materials is also carried out [10, 11, 12, 13,
14]. Simulation of the work of the connection under load in the modern design complex was carried out using the recommendations of the current and modern teaching aid [15].

3. Materials and methods

The requirements for composite material for strengthening and restoring existing wooden structures are determined by the tasks of its application: 1. The possibility of forming a composite on an uneven surface of existing wooden structures; 2. Providing adhesion to the surface of the wooden element; 3. Ensuring equal strength with wood - i.e. Strength characteristics of the composite material should not be lower than the corresponding strength indices for timber of building structures; 4. Provision of a modulus of elasticity of the composite material is close to the elasticity modulus of wood, in contrast to CFRP, to uniformly incorporate the composite material into the work throughout the contact surface and to reduce the effect of redistribution of stresses in the adhesive layers in time.

The samples adopted in the article are used for a long time by the authors of the article and represent the standard and most common in the construction of joints of wooden structures [4, 5, 6, 8, 9].

The specified list of requirements corresponds to a composite material (CM), made on the basis of glass fabric with an orthogonal cell of plain weave and a matrix based on epoxy resin ED-20. This material should be obtained from several layers of fiberglass, impregnated with a binder, layered laying on the contact surfaces of wooden elements simultaneously with the formation of the joint. Composite material in the structure of a wooden structure is a multilayer fiberglass of a certain thickness, each layer in which is reinforced with glass fibers in two mutually perpendicular directions. The direction of the reinforcement is determined by the direction of the layout of the fiberglass on the wooden structure, when the direction of the “base” of the fabric coincides with the direction of the shearing force in the jointing seam and the direction of the fibers of the joined wooden elements. Adhesive bond KM with wooden elements is created during the curing of the matrix simultaneously with the formation of the composite material.

To determine the physico-mechanical characteristics of the CM, the samples of the material were tested with a static load. The determination of the basic strength and elastic characteristics of the CMs corresponding to the work of the material in the joint was carried out, incl. Compressive strength, tensile strength, transverse bending and shearing; modulus of elasticity during compression, stretching and transverse bending; poisson's ratios.

In its structure, the CM being investigated is orthotropic, in connection with which the investigated characteristics were determined in two mutually perpendicular directions X and Y, coinciding with the directions of material reinforcement.

The tests for the determination of the time resistances were carried out in the loading mode with increasing load, in determining the elastic characteristics of the CM by the method of sixfold loading and unloading between the lower and upper loading limits, which constitute 5% and 25% of the destructive load, respectively. At the same time, relative deformations of the samples were measured on the lower and upper limits of loading by load cells with a base of 5 mm (for compression) and 20 mm (in tension). To determine the modulus of elasticity of CM during transverse bending, deformations (deflections) of samples in the middle of the flight were measured by a dial gauge with a 0.01 mm dividing point. Moduli of elasticity and coefficients of transverse strain in the compression and tension tests were determined: $E_p=\Delta \sigma_x/\Delta \varepsilon_x$, $E_y=\Delta \sigma_y/\Delta \varepsilon_y$, $\mu_{XY}=\Delta \varepsilon_x/\Delta \varepsilon_y$, $\mu_{XY}=\Delta \varepsilon_y/\Delta \varepsilon_x$, where $\Delta \varepsilon_x$, $\Delta \varepsilon_y$ – relative longitudinal deformations of the specimen under the action of stress respectively in the direction of the X and Y axis of the composite material; $\Delta \sigma_x$, $\Delta \sigma_y$ – increments of the normal stress from the lower to the upper limits of loading in the direction of the longitudinal axis of the sample, $\Delta \varepsilon_{Xlong}$, $\Delta \varepsilon_{Ylong}$, $\Delta \varepsilon_{Xtrans}$, $\Delta \varepsilon_{Ytrans}$ – relative longitudinal and transverse strains of the sample in the direction of the X-axis and Y for CM. The elastic modulus at bending was determined: $E_b = 0.01775 \cdot (\Delta P \cdot \Delta L^3) / (I \cdot \Delta \varepsilon)$, where $\Delta P$ - load force of the sample, equal to the difference between the upper and lower limits of loading; $\Delta \varepsilon$ is the deflection value of the sample, equal to the difference in
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deflections between the upper and lower loading limits; L, I - respectively, the span and the moment of inertia of the cross section of the sample.

4. Results

The analysis and volume of the processed material was based on the experience of specialists in the testing of joints of wooden structures [1, 2, 3, 7]. To compare the mechanical characteristics of the composite material with the structural pine wood with the wood moisture content \( W = 12\% \), the above diagrams of the CM work on compression and stretching are plotted (Pic.1), where the relative deformations of the material are plotted along the abscissa axis, and the ordinate is relative stresses \( \varphi \), expressed in fractions of the strength of the CM. Up to the level of the upper limit of the elastic work area of the tensile and compressive specimens at relative stresses not exceeding \( \varphi \leq 0.55 \), the graphs have a slight curvature and can, as in the case of pine wood, be assumed to be conditionally rectilinear. When the CM is applied to compression, the relative deformation at the level \( \varphi = 0.55 \) is \( \varepsilon = 0.32-0.35\% \), while tensile work is 0.9%. At compressive stresses close to destructive, the relative deformations of the composite material were 0.68-0.8\%, which corresponds to pine wood, for which the relative deformations during compression along the fibers in the pre-fracture stage are 0.6-0.8\%. At tensile stresses close to those destroying, the relative deformations of the CM were \( \varepsilon = 1.98\% \); for pine wood, the relative tensile strains along the fibers in the pre-fracture stage are 0.8-1.5\%. The analysis and volume of the processed material was based on the experience of specialists in testing joints of wooden structures.

Figure 1. The diagrams of the operating of CM: 1-compression, 2-stretching.
According to the results of compression, tensile, bending and shearing tests, the effect of a set of strengths by an epoxy matrix during curing at 18-20 °C on the strength and elastic characteristics of CM was evaluated. For this test, the same samples were run 10, 20, 30 and 60 days after manufacture. The results of tests of samples on the main types of stress state, characteristic for the work of compounds - compression, stretching, bending and shearing - are presented in Table 1, the kinetics of the strength set of the composite material for the main types of stress state - in Figure 2.

Table 1

The results of testing samples of composite material taking into account the direction of reinforcement

| Stress-strain state type | Index | Unit | Number of samples | Average, at the curing time of the epoxy matrix, days |
|-------------------------|-------|------|-------------------|---------------------------------------------------|
|                         |       |      |                   | 10       | 20       | 30       | 60       |
| Compression             |       |      |                   |          |          |          |          |
| σx                      | MPa   | 11   | 58.83             | 72.62    | 75.87    | 78.96    |          |
| σy                      | MPa   | 9    | 49.98             | 67.49    | 73.46    | 77.81    |          |
| (σx - σy)               | % from σx |   | 8.85              | 5.13     | 2.41     | 1.15     |          |
| Ex                      | MPa   | 11   | 7741              | 8794     | 9984     | 12977    |          |
| Ey                      | MPa   | 9    | 6359              | 7989     | 8958     | 12443    |          |
| (Ex - Ey)               | % from Ey |   | 1382              | 805      | 1026     | 71       |          |
| Extension               |       |      |                   |          |          |          |          |
| σx                      | MPa   | 7    | 140.15            | 173.00   | 180.74   | 188.1    |          |
| σy                      | MPa   | 7    | 121.09            | 159.66   | 168.37   | 173.6    |          |
| (σx - σy)               | % from σx |   | 19                | 13       | 12       | 15       |          |
| Ex                      | MPa   | 7    | 8645              | 9631     | 10461    | 13252    |          |
| Ey                      | MPa   | 7    | 7036              | 8646     | 9799     | 12260    |          |
| (Ex - Ey)               | % from Ey |   | 1608              | 985      | 662      | 992      |          |
| Bending                 |       |      |                   |          |          |          |          |
| σx                      | MPa   | 15   | 158.42            | 172.45   | 179.7    | 182.31   |          |
| σy                      | MPa   | 12   | 135.22            | 160.45   | 172.9    | 174.74   |          |
| (σx - σy)               | % from σx |   | 23.20             | 12.01    | 6.76     | 7.57     |          |
| Ex                      | MPa   | 15   | 10739             | 11690    | 12086    | 12999    |          |
| Ey                      | MPa   | 12   | 8662              | 10372    | 11181    | 11787    |          |
| (Ex - Ey)               | % from Ey |   | 2077              | 1318     | 905      | 1212     |          |
| Spalling                |       |      |                   |          |          |          |          |
| τx                      | MPa   | 12   | 10.43             | 13.45    | 14.36    | 15.54    |          |
| τy                      | MPa   | 11   | 10.04             | 13.32    | 14.3     | 15.5     |          |
| (τx - τy)               | % from σx |   | 0.39              | 0.13     | 0.06     | 0.04     |          |

From the consideration of the graphs in Pic. 2 we see that the strength and deformation characteristics increase in time, which is characteristic of the epoxy matrix, which is the basis of the studied composite material.
The compressive strength of the composite material for 10 days of curing the epoxy matrix was 47-63 MPa, in the mean along the X axis of the material, $\sigma_X = 58.8$ MPa, in the direction of the Y axis, $\sigma_Y = 49.98$ MPa, which is higher than the temporary resistance of pine wood to compression along the fibers $R_{\text{temps}} = 31 \div 44$ MPa). The compressive strength was mainly stabilized after 30 days of hardening of the material, finally in 60 days. In this case, the strength of CM for 60 days curing epoxy matrix was 74 - 83 MPa and reached an average in the direction of the X axis - $\sigma_X = 79$ MPa, along the Y axis, $\sigma_Y = 77.8$ MPa, respectively. The intensity of the CM strength set for compression was within 10 days from the moment of manufacture $5 \div 5.9$ MPa / day, during the next 10 days - $1.4 \div 1.75$ MPa / day, during the next 30 days (for a period of 20 Up to 30 days from the moment of manufacture of CM) – $0.33 \div 0.6$ MPa / day, during the next 30 days (from 30 to 60 days from the moment of manufacture of CM) – $0.10 \div 0.15$ MPa / day. The modulus of elasticity under compression of the CM for 10 days of curing the epoxy matrix averaged $E_X = 7741$ MPa, $E_Y = 6359$ MPa, which does not exceed the elastic modulus of the pine wood ($E_w = 10000$ MPa), comparable to that achieved by the composite material over 35 days of curing the matrix (curve 1 in Figure 2). After 10 days of matrix curing, the intensity of growth of the modulus of elasticity of CM on the compression stabilized, in the interval from 30 to 60 days an average of 100 MPa / day and is linear. After 60 days of curing the epoxy matrix, the modulus of elasticity of CM under compression was $E_X = 12977$ MPa, $E_Y = 12443$ MPa, which exceeds the elastic modulus of pine wood ($E_w = 10000$ MPa) by 1.24-1.3 times. The presented results show that when working on compression, the composite material for 10 days

![Figure 2](image-url)
accumulates strength sufficient for safe work in the structure: the temporary resistance of the composite material is 1.14 times higher than the corresponding values of pure wood.

The extension strength of the composite material during the 10 days curing of the epoxy matrix averaged along the x-axis direction of the material $\sigma_x = 140$ MPa, in the direction of the Y axis, $\sigma_y = 121$ MPa, which is higher than the temporary resistance of pine wood to stretching along the fibers ($R_{temp} = 100$ MPa) in 1.2-1.4 times. The tensile strength was mainly stabilized after 30 days of hardening of the material, finally in 60 days. In this case, the strength of the CM for 60 days of curing the epoxy matrix was 137-220 MPa and reached an average in the direction of the X axis - $\sigma_x = 188$ MPa, along the Y axis, $\sigma_y = 173$ MPa, respectively. The intensity of the tensile strength CM set for 10 days from the moment of manufacture was $12 \div 14$ MPa / day, during the next 10 days $3.2 \div 3.9$ MPa / day, during the next 10 days (for the period from 20 to 30 days from the moment of manufacturing of CM) $0.77 \div 0.87$ MPa / day, within the next 30 days (from 30 to 60 days from the moment of manufacture of CM) $0.17 \div 0.25$ MPa / day. The tensile modulus of the CM in the 10 days curing of the epoxy matrix averaged $E_x = 8644$ MPa, $E_y = 7036$ MPa, which does not exceed the elastic modulus of the pine wood ($E_w = 10000$ MPa), comparable to that achieved by the composite material over the 29 days curing of the matrix (Curve 2 in Figure 2). After 60 days of matrix curing, the intensity of growth of the modulus of elasticity of the tensile modulus stabilized, averaging 82-93 MPa / day and is linear in nature. After 60 days of curing the epoxy matrix, the modulus of elasticity of the CM under tension was $E_x = 13252$ MPa, $E_y = 12260$ MPa, which exceeds the elastic modulus of pine wood ($E_w = 10000$ MPa) by 1.23-1.32 times. The presented results show that, during tensile work, the composite material for 10 days accumulates strength sufficient for safe operation in the structure: the temporary resistance of the composite material is 1.2 to 1.4 times higher than the corresponding values of pure wood.

The bending strength of the composite material for 10 days of curing the epoxy matrix was 123-183 MPa, on the average in the x-direction of the material $\sigma_x = 158.4$ MPa, in the direction of the Y axis $\sigma_y = 135.2$ MPa, which is higher than the temporary resistance of pine wood to bending $= 80$ MPa). The flexural strength was mainly stabilized for 35-40 days of hardening of the material, finally after 60 days. In this case, the strength of CM for 60 days curing epoxy matrix was 171 - 198 MPa and reached an average in the direction of the X axis - $\sigma_x = 182$ MPa, along the Y axis, $\sigma_y = 174.7$ MPa, respectively. The intensity of the KM strength set for bending was within 10 days from the moment of manufacture $13 \div 16$ MPa / day, during the next 10 days $1.4 \div 2.5$ MPa / day, during the next 10 days (for the period from 20 to 30 days from the moment of manufacture of CM) $0.7 \div 1.2$ MPa / day, within the next 30 days (from 30 to 60 days from the date of manufacture of CM) no more than 0.09 MPa / day. The modulus of elasticity at bending of CM for 10 days of curing epoxy matrix averaged $E_x = 10739$ MPa, $E_y = 8644$ MPa, which corresponds to the elastic modulus of pine wood ($E_w = 10000$ MPa) comparable to that achieved by the composite material in 12 days curing of the matrix (curve 3 in Figure 2). After 10 days curing of the matrix, the intensity of growth of the modulus of elasticity of the CM on the bend stabilized, in the interval from 30 to 60 days averaged 20-30 MPa / day and is linear. After 60 days of curing the epoxy matrix, the modulus of elasticity of CM under compression was $E_x = 12999$ MPa, $E_y = 11787$ MPa, which exceeds the elastic modulus of pine wood ($E_w = 10000$ MPa) by 1.18-1.3 times. The presented results show that when working on bending, the composite material for 10 days accumulates strength sufficient for safe work in the structure: the temporary resistance of the composite material is 1.7 times higher than the corresponding values of pure wood.

The shear strength of the composite material for 10 days curing of the epoxy matrix was 7.9 - 14 MPa, in the mean along the X axis of the material $\sigma_x = 10.4$ MPa, in the direction of the Y axis, $\sigma_y = 10.04$ MPa, which is higher than the time resistance of wood chipping along the fibers ($R_{temp} = 7$ MPa). The shear strength was mainly stabilized for 35-40 days of hardening of the material, finally after 60 days. In this case, the strength of CM for 60 days curing epoxy matrix was 13-18 MPa and reached an average in the direction of the X axis and along the Y axis, $\sigma_x = \sigma_y = 15.5$ MPa. The intensity of the CM strength set for shearing made within 10 days from the moment of manufacturing
1 MPa / day, during the next 10 days - 0.3 MPa / day, during the next 10 days (for a period of 20 to 30 days from the date of manufacture of CM) - 0.1 MPa / day, during the next 30 days (from 30 to 60 days from the date of manufacture of CM). The presented results show that when working on shearing, the composite material for 10 days of accumulation is sufficient for safe work in the structure: 1.4 times higher than the corresponding values of pure wood.

From the consideration of table 1 it follows that with an increase in the curing time of the epoxy matrix, the difference between the homogeneous characteristics of the composite in two mutually perpendicular directions X and Y decreases from 15-19% at the level of 10 days to 1-4% at the level of 60 days of curing of CM. It was established by statistical methods that at 60 days of hardening the CM for each type of stress state the difference between the strength characteristics in the X direction of the material and in the Y direction of the material is not reliable, and therefore the strength and deformability in the X and Y directions for each The form of the stressed state can be combined into one aggregate. Table 2 presents the results of statistical processing of combined strength and deformation characteristics at the age of an epoxy matrix of 60 days for each of the investigated types of stress state of the composite material.

**Table 2**

| No | Stress-strain state type | Statistics of statistical processing | Unit | Strength limit, σsl | Elastic modulus, Е |
|----|--------------------------|--------------------------------------|------|---------------------|-------------------|
| 1  | Compression              | Number of units, n                  | Pc   | 20                  | 20                |
| 2  |                          | Average, M                          | MPa  | 78.44               | 12737             |
| 3  |                          | The average square deviation, S      | MPa  | 8.89                | 1914              |
| 4  |                          | Variational coefficient, V          | %    | 11.3                | 15.0              |
| 5  |                          | Mean error of the arithmetic mean, m | MPa  | 1.99                | 428               |
| 6  |                          | Accuracy rate, P                    | %    | 2.53                | 3.4               |
| 1  | Extension                | Number of units, n                  | Pc   | 14                  | 14                |
| 2  |                          | Average, M                          | MPa  | 181.4               | 12785             |
| 3  |                          | The average square deviation, S      | MPa  | 21.84               | 809.9             |
| 4  |                          | Variational coefficient, V          | %    | 12.1                | 6.33              |
| 5  |                          | Mean error of the arithmetic mean, m | MPa  | 6.06                | 224.6             |
| 6  |                          | Accuracy rate, P                    | %    | 3.34                | 1.76              |
| 1  | Bending                  | Number of units, n                  | Pc   | 27                  | 27                |
| 2  |                          | Average, M                          | MPa  | 178.9               | 12460             |
| 3  |                          | The average square deviation, S      | MPa  | 14.27               | 1897              |
| 4  |                          | Variational coefficient, V          | %    | 8                   | 15.2              |
| 5  |                          | Mean error of the arithmetic mean, m | MPa  | 2.747               | 365.1             |
| 6  |                          | Accuracy rate, P                    | %    | 1.54                | 2.93              |
| 1  | Spalling                 | Number of units, n                  | Pxc  | 23                  | -                 |
| 2  |                          | Average, M                          | MPa  | 14.85               | -                 |
| 3  |                          | The average square deviation, S      | MPa  | 1.94                | -                 |
| 4  |                          | Variational coefficient, V          | %    | 13.06               | -                 |
| 5  |                          | Mean error of the arithmetic mean, m | MPa  | 0.404               | -                 |
| 6  |                          | Accuracy rate, P                    | %    | 2.72                | -                 |

Based on the obtained characteristics, numerical modeling of the work of joining the composite material with wood (CM-connections) in the ABAQUS software complex was performed. The use of this software package is justified by the availability of a worthy and complete textbook [15]. For the finite element model, the design of a symmetrical two-sided sample was adopted, on which natural experiments were conducted to study the stress-strain state of CM compounds. The non-linear
formulation of the calculation made it possible to determine theoretically the upper limit of the region of elastic work of the compounds. Stress-strain state of the composite in the sample - normal stresses and deformations - at the level of the calculated bearing capacity of the compound is shown in Pic.3. When the sample is loaded, corresponding to the design load-bearing capacity of the joint, the maximum compressive stresses occurring along the welded joint of the sample are \(\sigma_{cm} = 6.3 \div 7.9\) MPa <\(\sigma_{min} = 51.7\) MPa. The actual strength of the composite material is sufficient to work in joins of wooden elements. In this case, the calculated deformations of the joint, defined as the deformation of the mutual displacement of the joined wooden elements, will be \(D = 0.04\) - 0.06 mm.

**Figure 3.** Calculation of the CM connection in the Abaqus: a-normal stresses in CM-sticking, MPa; b-vertical deformations of CM connection, mm.

### 5. Discussion

One of the basic requirements for a composite material intended for strengthening wooden structures is the strength with wood. Accepting for defective minimum the standard resistance of pure pine wood, we compare with these values the minimum possible strength characteristics of CM for each type of stress state. The results are shown in table 3.

| No | Stress-strain state type | Material Composite material | Wood Rn, MPa | Comparison \(\sigma_{min}\) and Rn |
|----|--------------------------|-----------------------------|--------------|----------------------------------|
|    |                          | M, MPa                      | 3*S, MPa     | \(\sigma_{min}\), MPa           |
|    |                          | 78.44                       | 26.67        | 51.77                            | \(\sigma_{min} > Rn\) in 1.57 times |
| 1  | Compression              | 181.4                       | 65.52        | 115.88                           | \(\sigma_{min} > Rn\) in 1.93 times |
| 2  | Stretching               | 178.9                       | 42.81        | 136.09                           | \(\sigma_{min} > Rn\) in 2.39 times |
| 3  | Bending                  | 14.85                       | 5.82         | 9.03                             | \(\sigma_{min} > Rn\) in 1.98 times |

From the consideration of table 3 it follows that the main types of stress state that occur in the work of compounds of composite material with wood - compression, stretching, crushing and shearing - statistically established minimum possible strength characteristics of composite material are greater than the corresponding standard resistances of clean wood in 1.57 - 2.39 times.
6. Conclusions
Based on the tests carried out and the calculations performed, the following conclusions and suggestions are made:

1. A composite material based on an epoxy matrix and glass fabric is proposed, which can be formed directly on the surface of wooden elements and used to strengthen wooden structures.

2. Calculated characteristics - temporary resistances and moduli of elasticity of composite material - are determined for the main types of stressed state, characteristic for the work of the material in the joints of wooden elements - compression, stretching, bending and shearing.

3. The kinetics of the strength and deformation characteristics of a composite material is considered. It is established that within 10 days the composite material acquires strength sufficient for safe operation in joints of wooden structures. In this case, the temporary resistance of the composite material to compression, stretching, bending and shearing is 1.2 to 1.4 times higher than the corresponding values of pure wood. Strength and modulus of elasticity on compression, stretching and bending, shear strength are stabilized for 35-40 days curing epoxy matrix.

4. Statistical indices of the variability of the strength and deformation characteristics of a composite material are determined. On the basis of statistical analysis it is established that the minimum possible strength indexes of composite material are greater than the corresponding normative resistances of clean wood in 1.57 -2.39 times.

5. Calculations performed by numerical methods in the ABAQUS software package, using the example of a symmetrical two-sliced sample, showed that the design stresses in the compound composite at the level of the design load-bearing capacity of the joint are 5-8 times less than the actual strength characteristics of the composite material.

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