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BONDING PERFORMANCE OF MUF AND PUR ADHESIVES FOR GLUED LAMINATED TIMBER

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ABSTRACT: Most adhesive systems for the production of glued laminated timber (GLULAM) are designed for softwoods and are therefore often not suitable for bonding hardwoods such as beech. Despite its good mechanical properties, beech wood still has a lot of untapped potential in timber construction. It has a high density and strength, but at the same time is not biologically durable and is dimensionally unstable. Beech wood can be successfully bonded with typical wood adhesives, but problems often occur in delamination tests due to unfavourable shrinkage and swelling when the bonded components are exposed to moisture fluctuations or immersed in water. The aim of this study was to determine the bonding performance of common melamine-urea-formaldehyde (MUF) and polyurethane (PUR) adhesives in the production of spruce GLULAM when applied to beech GLULAM or hybrid beech and spruce GLULAM. The experiment was divided into two parts. In the first part, beech lamellas were bonded with MUF, PUR and PUR in combination with a primer (PUR+P) to form a GLULAM. In the second part, hybrid GLULAMs made of beech and spruce were produced. The two outer lamellas were made of beech wood, while the three inner ones were made of spruce wood. For beech GLULAM only, all adhesive bonds were found to have a much higher shear strength (about 14 N/mm^2) than required by the standard [1]. All adhesive bonds in a hybrid GLULAM made of beech and spruce also met the requirements, but the shear strength was lower (about 10 N/mm^2). Adhesive bonds between spruce and beech achieved slightly higher average strength values than adhesive bonds between spruce only. The highest shear strengths were achieved with PUR adhesives in combination with a primer, followed by MUF and PUR adhesives without primer. The results show that beech and spruce wood can be successfully bonded to form a hybrid beam using MUF and PUR adhesives. The adhesive bonds between beech and spruce wood show an effective bonding performance and fulfil the standard requirements.

KEYWORDS: adhesives, beech, glulam, shear strength, spruce

1 - INTRODUCTION

In view of growing environmental awareness and the global shift towards sustainable construction, wood has emerged as an increasingly attractive alternative to steel and concrete in recent years. In Europe, softwood is predominantly used for construction. However, climate change, which results in higher average annual temperatures, changes in the distribution of rainfall and some other factors are changing the composition of Slovenian forests and leading to greater availability of hardwood, especially beech (*Fagus sylvatica* L.) and recucing the relative proportions of spruce (*Picea abies* (L.) Karsten) in forests [2].

Despite its potential, the use of hardwood in construction faces major challenges, such as lack of standardization, limited expertise and the complexity of integration into existing technological processes. It is expected that these limitations will be overcome in the future and new opportunities for the use of hardwood will emerge. Beech wood offers higher strength and stiffness compared to softwood, but also has some disadvantages such as higher costs, dimensional instability, lower biological resistance and higher requirements for mechanical processing and drying. Some of the less advantageous properties of beech wood can be partially mitigated by processing it into laminated veneer lumber (LVL), but this requires a rather complex technological process.

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By combining beech and softwood, it is possible to utilize the strengths of both materials and at the same time mitigate their respective weaknesses. This synergy can be achieved through the production of hybrid glued laminated beams, in which several lamellas of different wood species are glued together to form a single structural element. Such an approach not only maximizes the potential of beech wood, but also expands the scope for the use of wood in modern construction practice [2].

2 - BACKGROUND

2.1 BEECH AS STRUCTURAL TIMBER

Beech wood has a significantly higher strength than spruce wood and enables the production of glulam with smaller cross-sections. This leads to slimmer and more aesthetically appealing structural designs. The modulus of elasticity of beech wood is between 14,000 and 16,000 N/mm^2, while spruce wood is between 10,000 and 11,000 N/mm^2 [3]. Beech wood can be used to produce laminated timber of higher strength classes such as GL 40 (characteristic bending strength of 40 N/mm^2) and GL 48 [4], in contrast to spruce wood, which is typically used for strength class GL 24 (characteristic bending strength of 24 N/mm^2, C24 class for lamellas) [5]. In addition, beech wood is also used for the production of LVL, which achieve bending and tensile strengths of up to 70 N/mm^2. These beams are very homogeneous and offer excellent structural properties. However, due to the limited natural resistance of beech wood to biodegradation, construction elements made of beech are mainly used in service class 1 [6]. There are also innovative developments, such as beech cross-laminated timber (CLT) panels and hybrid beams, where materials are combined to place optimal resources in optimal locations and improve performance [7].

According to EN 14080, glued laminated timber (GLULAM) have higher characteristic compressive strengths than tensile strengths. In such beams, failure occurs on the tensile side, typically at knots or finger joints, leading to sudden and brittle failure [8]. Consequently, laminated beams are commonly reinforced on the tensile side to enhance stiffness and bending strength. Reinforcements may include polymer fibers, sheet metal, or wood composites. Heavily tensile-reinforced beams can experience compression failure, which is more ductile and predictable [9]. Reinforcing both sides increases bending strength and stiffness by enhancing the moment of inertia but can lead to higher shear stresses, particularly near the neutral axis of beams. The outer laminations have the greatest impact on stiffness, as stresses are highest there. High-stiffness lamellas are most effective when placed in the outermost layers, acting like flanges in I-beams, while the core primarily absorbs shear stresses [10]. In beams made from different wood types with varying modulus of elasticity, stress distribution depends on the lamella's distance from the neutral axis and stiffness. This can result in maximum stress and failure occurring in intermediate layers rather than the outermost ones.

2.2 ADHESIVES FOR THE PRODUCTION OF GLUED LAMINATED PRODUCTS

In Europe, melamine-urea-formaldehyde (MUF) and one-component polyurethane (PUR) adhesives are the most commonly used for GLULAM production. LVL is typically bonded with phenol-formaldehyde (PF) or phenol-resorcinol-formaldehyde (PRF) adhesives, while CLT is most often glued with one-component PUR adhesives. A key distinction between formaldehyde-based and isocyanate-curing adhesives lies in the elasticity or ductility of their bonded joints. Formaldehyde-based adhesives, such as MUF, PF and PRF, produce highly cross-linked, brittle bonds with a high modulus of elasticity after curing. In contrast, polyurethane adhesives can be formulated to exhibit a wide range of elasticity, from very low to very high. For optimal wood bonding, it is recommended that the adhesive's modulus of elasticity matches that of the wood. This alignment ensures better stress distribution across the adhesive joint and the wood, reducing the likelihood of fractures while maintaining high breaking strengths [11]. Unlike brittle adhesives, this approach prevents the stress from concentrating solely in the wood, instead distributing it evenly between the wood and adhesive joint.

Adhesive systems for structural bonding are typically designed for softwoods, which can make them unsuitable for hardwood species like beech. Challenges often arise during delamination tests due to high modulus of elasticity and its unfavourable shrinkage and swelling properties of beech wood [12]. Additionally, the anatomical structure of beech can result in poor adhesive bonds if the adhesive is not properly adapted [13].

The aim of this study was to determine the bonding performance of common melamine-urea-formaldehyde (MUF) and polyurethane (PUR) adhesives in the production of spruce GLULAM when applied to beech GLULAM or hybrid beech and spruce GLULAM. The shear strength and the delamination of adhesive bonds were determined.

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3 – PROJECT DESCRIPTION

3.1 BEECH GLULAM

The experiment was divided into two parts. In the first part, beech wood (*Fagus Sylvatica* L.) was glued with structural adhesives to form a laboratory-scale GLULAM with external dimensions of 105 mm x 100 mm x 600 mm using four 25 mm thick lamellas (Figure 1).

The following adhesives were used:

- MUF = Melamine-urea-formaldehyde adhesive DYNEA PREFERE 4535 with hardener 5046
- PUR = polyurethane adhesive LOCTITE HB S209 PURBOND
- PUR+P = Polyurethane adhesive LOCTITE HB S209 PURBOND with primer PURBOND PR 3105

The bonding parameters for beech GLULAM are listed in Table 1.

After gluing, the shear test specimens were cut and conditioned for two weeks in a standard climate (i.e. temperature (T) 20 °C and relative humidity (RH) 65%) in accordance with [1]. Half of the specimens were impregnated with water in a pressure vessel (0.5 hours at 0.85 bar, 2 hours at 6 bar) and dried at 70 °C to the original mass.

3.2 HYBRID BEECH-SPRUCE GLULAM

In the second part, hybrid GLULAMs with external dimensions of 105 mm x 100 mm x 520 mm were produced using five 20 mm thick lamellas. The two outer lamellas were made from beech wood, while the three inner ones were made of spruce (*Picea abies* (L.) Karst) wood (Figure 2). The spruce and beech wood used was free of knots, red heartwood or other anomalies. The average moisture content of spruce and beech wood was 10% and 8.1% respectively.

The following adhesives were used:

- MUF = Melamine-urea-formaldehyde adhesive DYNEA PREFERE 4535 with hardener 5046
- PUR+P = polyurethane adhesive LOCTITE HB S109 PURBOND with primer PURBOND PR 3105

The MUF adhesive was prepared with a mass ratio of 100 parts of resin to 30 parts of hardener. The adhesive meets the requirements of EN 301:2013 Type 1 [14] and is classified as a general purpose and finger-jointing adhesive suitable for both mixed and separate applications. It can effectively bond various softwoods and hardwoods, such as birch and beech. The resin has a solids content of 63–65%.

The PUR+P adhesive was a liquid one-component polyurethane adhesive with 100% solids content. The adhesive hardens in reaction with air and wood moisture and forms a non-brittle bond. The minimum required moisture content of the wood is 8%. The adhesive is certified as Type 1 according to EN 15425:2017 [15]. As the manufacturer of the PUR adhesive prescribes a primer for bonding beech wood, a primer was applied to two of the bonds between beech and spruce lamellas, but not to the other two bonds between spruce lamellas. The primer concentrate was mixed with water to form a 10% solution (by weight). The bonding parameters for beech-spruce hybrid GLULAM are listed in Table 2.

After gluing, the shear and delamination test specimens were cut and conditioned for two weeks in a standard climate (T = 20 °C, RH = 65%) in accordance with EN 14080:2013. For each adhesive, the tests comprised six specimens for the shear test and three specimens for the delamination test (Figure 3).

Figure 1. Beech GLULAM - assembly and cold pressing in hydraulic press.

Table 1: The bonding parameters for beech GLULAM

Adhesive	Adhesive Application	Primer Application	Primer Activation Time	Closed Assembly Time	Specific Clamping Pressure	Pressing Time	Curing Temperature
	(g/m²)	(g/m²)	(min)	(min)	(N/mm²)	(h)	(°C)
MUF	500	/	/	25	1,4	4,5	23
PUR	200	/	/	10	1,2	2,5	23
PUR+P	200	20	15	10	1,2	2,5	23

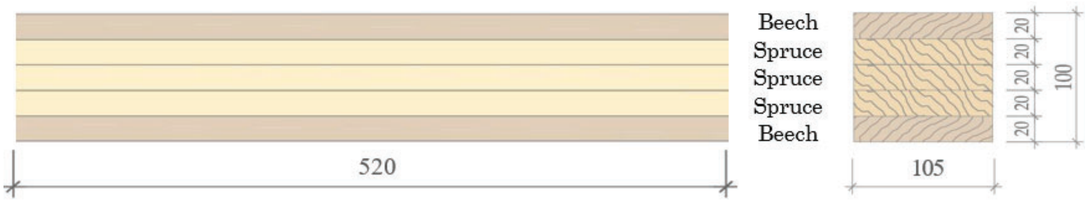

Figure 2. Beech-spruce hybrid GLULAM.

Table 2. The bonding parameters for beech-spruce hybrid GLULAM

Adhesive	Adhesive Application	Primer Application	Primer Activation Time	Closed Assembly Time	Specific Clamping Pressure	Pressing Time	Curing Temperature
	(g/m²)	(g/m²)	(min)	(min)	(N/mm²)	(h)	(°C)
MUF	400	/	/	25	1	19	23
PUR+P	150	20	25	9	1	19	23

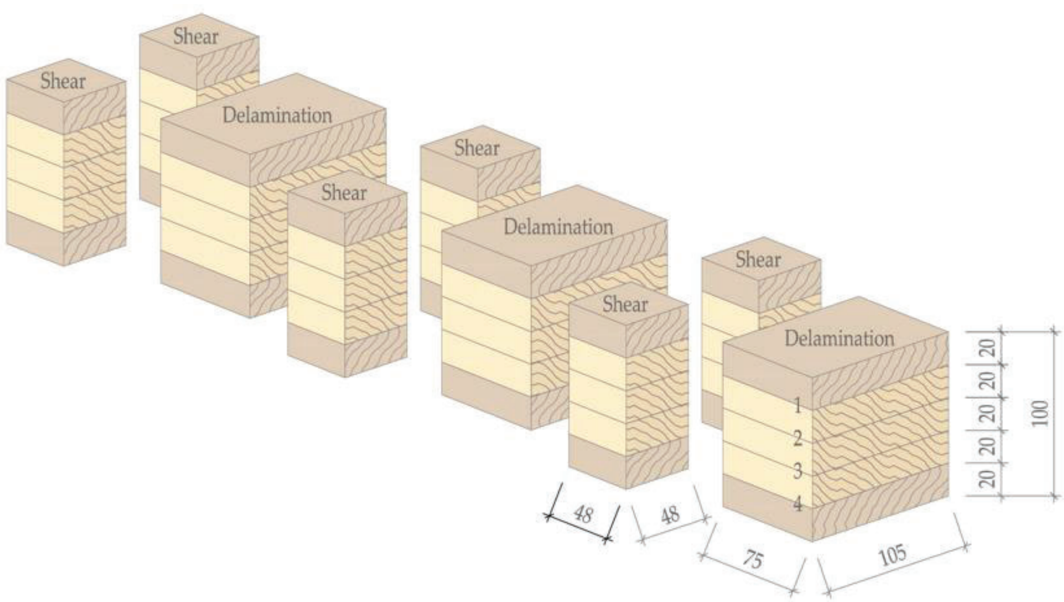

Figure 3. Dimensions (in mm) of specimens for the shear and delamination test with designation of glue lines 1, 2, 3 and 4.

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4 – EXPERIMENTAL SETUP

4.1 SHEAR TEST

The shear test was performed in accordance with standard EN 14080:2013 on a Zwick Roel Z100 testing machine. The specimens were placed in the testing machine so that the glue line was in the same plane as the loading jaws. The shear strength was determined using equation 1:

$$f_v = k * \frac{F_u}{A} \quad (1)$$

where

f_v is the shear strength (N/mm^2);

F_u is the ultimate load (N);

A is the sheared area (mm^2);

k factor: k=0.78+0.0044*t.

The factor k modifies the shear strength for specimens where the thickness (t) in the grain direction of the sheared area is less than 50 mm. The amount of wood failure (WF) percentage of broken glue lines was assessed visually and rounded off to the nearest number divisible by 5.

4.2 DELAMINATION TEST

The delamination test of glue lines was carried out in accordance with standard EN 14080:2013. The test cycle for method B was used. The total delamination and the maximum delamination were determined according to equations 2 and 3, respectively:

$$Delam_{tot} = 100 * \frac{l_{tot,delam}}{l_{tot,glue\ line}} \quad (2)$$

$$Delam_{max} = 100 * \frac{l_{max,delam}}{2 * l_{glue\ line}} \quad (3)$$

where

$Delam_{tot}$ is the total delamination (%);

$Delam_{max}$ is the maximum delamination (%);

$l_{tot,\ delam}$ is the total delamination length (mm);

$l_{tot,\ glue\ line}$ is the entire length of all glue lines on the two end-grain surfaces of each specimens (mm);

$l_{max,\ delam}$ is the maximum delamination length (mm);

$l_{glue\ line}$ is the length of one glue line (mm).

5 – RESULTS

5.1 SHEAR STRENGTH OF GLUE LINES OF BEECH GLULAM

The results of the shear strength and wood failure percentage of the glue lines of specimens conditioned in standard climate are shown in Table 3. The PUR+P and MUF adhesives showed the best bonding performance, achieving an average shear strength of 15.6 N/mm^2 and 13.9 N/mm^2, respectively. The average amount of wood failure was 100% for both adhesives. This means that both adhesives had a higher cohesive strength and adhesion between the adhesive and the wood than the cohesive strength of the wood.

When PUR adhesive was used without primer, the shear strength of the glue line was still high (e.g. 13.7 N/mm^2), but the average failure rate of the wood dropped to about half (e.g. 56%). The test specimens, whose results are shown in red, did not meet the requirements according to the EN 14080:2013 standard.

The results of the shear strength and wood failure percentage of the glue lines of specimens impregnated in water and dried back to the original mass are shown in Table 4. Again, the PUR+P and MUF adhesives showed the best bonding performance with an average shear strength of 8.9 N/mm^2 and 8.7 N/mm^2, respectively. The average amount of wood failure was 99% for the MUF adhesive and 50% for the PUR+P adhesive.

Both adhesives (i.e. MUF and PUR+P) met the standard requirements, while the glue lines of the PUR adhesive without primer did not. The average shear strength of the specimens after impregnation in water and drying back to the original mass was reduced to 5.1 N/mm^2, and the average amount of wood failure was 0%.

It was found that the bonding of beech GLULAM with PUR adhesives without primer is not sufficient. Further investigation of hybrid GLULAM made of beech and spruce lamellas therefore focused on bonding with MUF and PUR+P adhesives, while PUR adhesive without primer was only used in cases where spruce lamellas were bonded together (i.e. in the inner part of hybrid GLULAM).

Table 3: Shear strength and wood failure percentage of glue lines of specines conditioned in standard climate

Adhesive	MUF		PUR		PUR+P	
#	f_v (N/mm^2)	WF (%)	f_v (N/mm^2)	WF (%)	f_v (N/mm^2)	WF (%)
1	13.5	100	15.1	100	16.0	100
2	14.5	100	15.7	70	16.8	100
3	13.7	100	13.1	100	16.1	100
4	13.0	100	14.1	95	14.3	100
5	14.5	100	13.4	40	17.3	100
6	14.1	100	12.9	10	14.3	95
7	14.2	100	14.3	55	15.8	100
8	13.6	100	12.9	10	15.4	100
9	12.7	100	13.7	95	16.5	100
10	13.8	100	15.7	95	14.8	100
11	13.7	100	12.2	0	14.6	100
12	13.9	100	14.6	5	15.6	100
13	12.5	100	15.7	60	16.7	100
14	14.4	100	12.5	80	15.2	100
15	15.0	100	12.4	30	16.1	100
16	14.6	100	15	95	14.9	100
17	14.5	100	13.1	25	15.2	100
18	14.3	100	10.8	50	15.3	100
Average	**13.9**	**100**	**13.7**	**56**	**15.6**	**100**

Table 4: Shear strength and wood failure percentage of glue lines of specines impregnated in water and dried

Adhesive	MUF		PUR		PUR+P	
#	f_v (N/mm^2)	WF (%)	f_v (N/mm^2)	WF (%)	f_v (N/mm^2)	WF (%)
1	7.9	100	6.9	0	8.7	100
2	7.6	100	7.4	0	9.2	100
3	8.7	100	5.6	0	9.3	40
4	8.2	100	8	0	9.1	100
5	8.5	100	7.2	0	8.3	50
6	9.3	100	4.9	0	9.3	30
7	9.3	100	2.7	0	10.2	85
8	8.7	100	5.7	0	7.8	20
9	7.9	100	1.3	0	8.2	50
10	8.7	100	0.8	0	10	50
11	8.0	100	4.4	0	7.8	20
12	8.1	100	2.3	0	7	20
13	8.9	100	4.8	0	9.2	30
14	8.9	100	6.2	5	9.5	30
15	9.2	100	4.2	0	9	10
16	9.2	100	6.7	0	9.2	70
17	8.9	85	7.2	0	9.3	30
18	10.5	90	4.9	0	8.9	70
Average	**8.7**	**99**	**5.1**	**0**	**8.9**	**50**

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5.2 SHEAR STRENGTH OF GLUE LINES OF HYBRID GLULAM

The results of the average shear strength and average wood failure percentage of the glue lines of specimens conditioned in standard climate are shown in Table 5. All tested glue lines met the requirements of EN 14080:2013, which specifies a minimum average shear strength of 6 N/mm^2 with at least 90% wood failure. 100% wood failure was observed in all tested glue lines.

In glue lines between spruce and beech wood, failure occurred in both wood species. The position of the samples in the test jaws played a decisive role in whether the failure was initiated in beech or spruce wood. When failure occurred in beech wood, the shear strengths were slightly higher than when failure occurred in spruce wood, which is due to the higher shear strength of beech compared to spruce. Glue lines between spruce and beech achieved slightly higher strength values on average than glue lines between spruce only, but the differences were not significant [2].

5.3 DELAMINATION OF GLUE LINES OF HYBRID GLULAM

The requirements of the delamination test (method B) in accordance with EN 14080:2013 were met in all bonding cases. Figure 4 shows the specimens after the test, with no delamination visible between the glue lines. The bonds between beech and spruce wood also proved to be unproblematic. When using PUR adhesive alone and in combination with a PUR+P primer, no differences in delamination were found [2].

Table 5: Average shear strength and wood failure percentage of glue lines of hybrid GLULAM

Glue Line	Adhesive	f_v (N/mm^2)	WF (%)	Number of Specimens
1 (beech–spruce)	MUF	9.85	100	6
2 (spruce–spruce)	MUF	9.71	100	6
3 (spruce–spruce)	MUF	8.95	100	6
4 (spruce–beech)	MUF	10.2	100	6
1 (beech–spruce)	PUR+P	10.65	100	6
2 (spruce–spruce)	PUR	10.23	100	6
3 (spruce–spruce)	PUR	8.47	100	6
4 (spruce–beech)	PUR+P	9.58	100	6

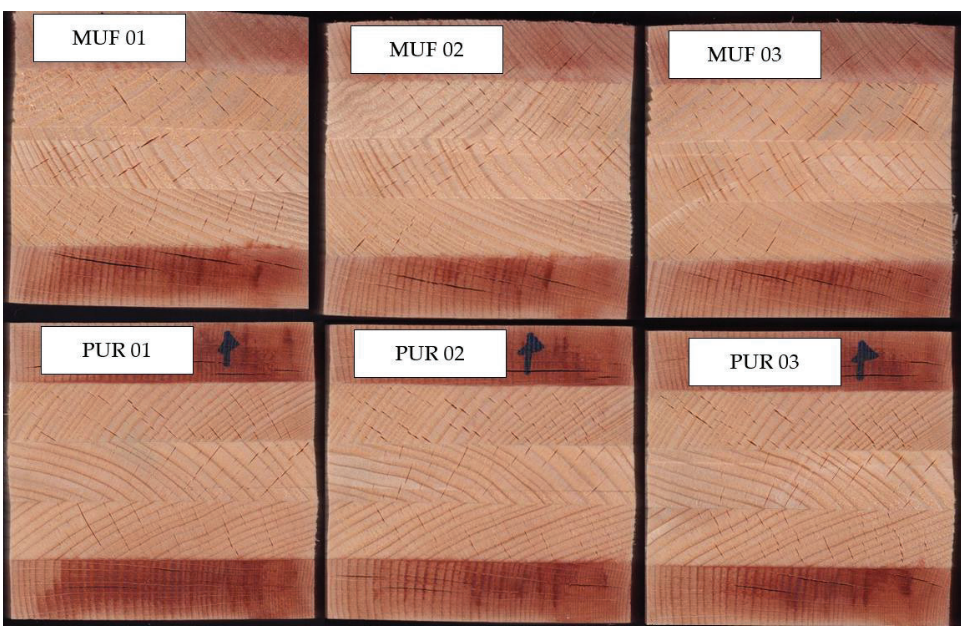

Figure 4. Specimens of hybrid GLULAM after the delamination test [2].

6 – CONCLUSION

The results of the shear and delamination tests of glue lines in this study allow the following conclusions to be drawn:

Bonding of beech GLULAM with MUF and PUR+P adhesives met the standard requirements for shear strength, while bonding with PUR adhesives without primer was not sufficient.

The use of MUF and PUR adhesives, without or in combination with a primer, for bonding hybrid GLULAM made of beech and spruce met the standard requirements of the shear and delamination test.

The results show that beech and spruce wood can be successfully bonded to form a hybrid beam. The bond line between beech and spruce wood is moisture-resistant and effectively transfers bending stresses.

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