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A New Type of Nail for Wooden Structures with Increased Resilience

Todor Penchev, Petar Bodurov, Pencho Sirakov, Dimitar Mihaylov
[1]*(Relo-Nail Ltd., Oborishte Str. 1/A/17, 1504 Sofia, BULGARIA, EUROPE)*
Corresponding Author: Petar Bodurov- pbodurov@mgu.bg

ABSTRACT :*In the following work, we present the results from a research of a type of nail with a new form of section, in comparison to the round section that currently used nails have. This new form is similar to an equilateral triangle, the sides of which' are curves [Reuleaux Triangle]. The body section of this new type of nail has three curves and three edges; his surface SR is with 5.56% larger than the surface SC of a round nail with the same section area. From the experimental research that has been made so far, it was established: (i) because of the larger compaction of the wooden material in the ends of the edges, and of the larger surface, you get a bigger friction force, resulting in a pulling-out force Fto,R that is on average twice as bigger as the pulling-out force Fto,C; (ii) because that the new form of nail has edges, this leads to bigger resistance during the rotating of the joined wooden elements one against another – the moment Mr is on average 60% bigger than the one with elements, joined with a normal nail. These advantages, as well as the use of the existing technology and machines for the production of nails without having to effect any major changes, create the conditions for the application of the new type of nail in construction, furniture production and in the everyday life, for an output of products with larger resistance to external forces. This effect will be especially useful for increasing the residential buildings' resilience during earthquakes, hurricanes and other natural disasters.*

KEYWORDS *nails, Reuleaux Triangle, wooden structures*

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I. INTRODUCTION

The production of nails worldwide is one of greatest in fabricated metal products: reinforcing bars – 400 million tons, sheet metal – 240 million tons, pipes – 60 million tons nails, and screws – 32 million tons in 2014 [1]. Nails are used for connecting elements of wooden constructions; the largest quantities are used for wooden-frame houses. The average wooden-frame house uses require between 20,000 and 30,000 nails of various types and sizes [2]. Earthquakes or hurricanes are considered as extreme conditions for those structures. A variety of nails is available for wooden structures, which are to be under heavy loading conditions – Fig. 1 [3], [4], [5].

Most of these nails have a number of advantages, compared to conventional nails, but they are difficult to be manufactured in the existing automatic machines for nails and have a higher price.

The new type of nail[10] has a section, known as the Reuleaux Triangle. This geometrical figure has a shape, formed from the intersection of three circles, each having its center at the vertex of a triangle

– Fig. 2. The radius R is equal to the length of the triangle's side. In Fig. 2 we see that the Reuleaux Triangle includes three curves and three edges.The Reuleaux Triangle can be seen as a closed convex curve of constant width. This is a type of curves which, when rotated in a square, make contact with all four sides [6]. The other definition is that of "curves of constant width that have the same "width" regardless of their orientation between the parallel lines" [7]. The surface – that is the curve with the largest area – also belongs to this type, while the Reuleaux Triangle is the closed curve with the smallest area, but with the same perimeter.

The more important qualities of the Triangle are:

- Its radius R = 2,112r, where r is the radius of a circle with the same area.
- With the same area, the perimeter of the Reuleaux Triangle PR is 5.56% larger than the perimeter PC of the given circle.
- The second moment of area I and the elastic section modulus S, when you have a circular section, are the same as regard to a coordinate system, passing through the center of gravity in the circle, therefore with a

cicle $I_{x,c} = I_{y,c}$, $S_{x,c} = S_{y,c}$. With the Reuleaux Triangle $I_{x,R} = I_{y,R}$, $S_{x,R} \neq S_{y,R}$ as regards to a coordinate system, passing through the section's center of gravity.
In agreement with the definition for S [8], [9] from Fig. 2b we can see that with the Triangle there are two elastic section modulus $S_{R,y}$ ($S_{R,y1}$, $S_{R,y2}$) and one elastic section modulus $S_{R,x}$:

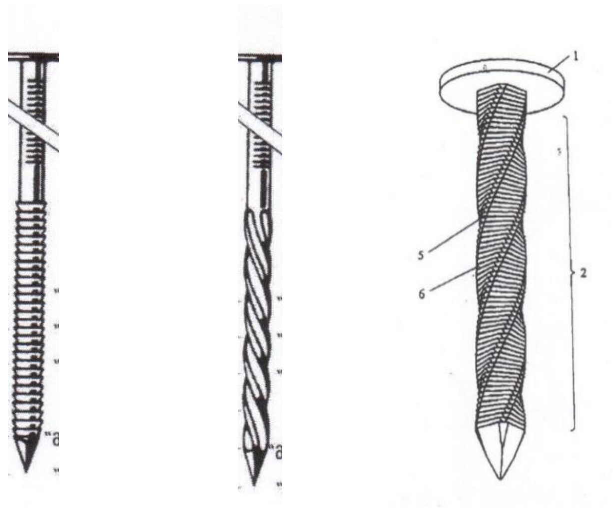
$$S_{(R,y1)}=I_y/b; \quad S_{(R,y2)}=I_y/a \; ; \; S_{(R,x)}=I_x/0.5R \qquad (1)$$

By looking at the geometric proportions in an equilateral triangle it can be determined that a = 0.577R , b = 0.423R and (1) becomes:

$$S_{(R,y1)}=I_y/0.423R; \; S_{(R,y2)}=I_y/0.577R; \; S_{(R,x)}=I_x/0.5R \qquad (2)$$

where [6]

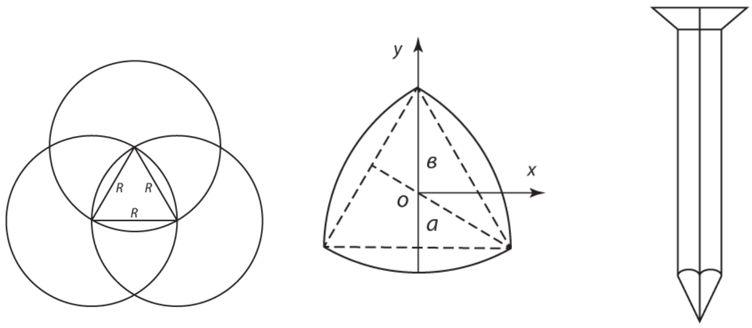
$$I_x=I_y=1/48(10\pi-17\sqrt{3})R^4 \qquad (3)$$



a) b) c)

Fig.1. Design of nails for heavy loading wooden structures:a - with rolled rings; b – with rolled screw channels; c – with screw canals and rings: 1- nail heat, 2 – nail body, 5 – screw cylindrical surface, 6 – linear rings

Here we present the results from our comparative experimental research for determining the maximal forces and moments, which impact wooden structures, the elements of which are to be joined with a nail with a round section, or a section of the Reuleaux Triangle type.



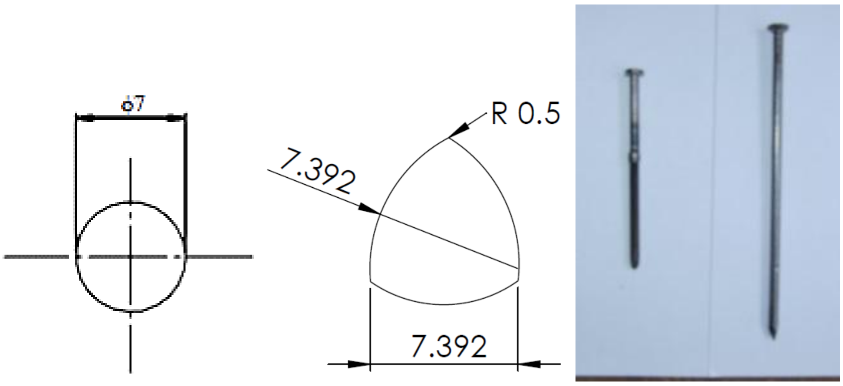
a) b) c)

Fig. 2. a – a Reuleaux Triangle; b – a scheme for determining the elastic section modulus S; c— a nail with a Reuleaux Triangle section

II. Methodics

A round section nail with the following characteristics: radius R_C = 3.5 mm, length L_C = 190 mm, area of the counter-section A = 38.46 mm^2, perimeter P_C = 21.98 mm, was used in the experiments. The nail with the Reuleaux Triangle section, was with the same area A, radius R_R = 7.392 mm, length of the section portion L_R = 85 mm (the length of the entire round section nail is 145 mm), perimeter P_R = 23.2 mm – Fig. 3;

his edges were rounded with radius R = 0.5 mm. There have been made 10 such nails, with the Reuleaux Triangle section portion been made on a filament erosion machine.
In Table 1. are given the values of the second moment of area I and the elastic section modulus S for the two types of nails.



a) b)

Fig. 3. Comparison of the ordinary and the new nails: a – comparison of the cross-section dimensions; b - view of the used nails with the new shape and ϕ7

Table 1. Value of I and S for ordinary and new nails

Section	I_x, mm^4	I_y, mm^4	$S_{y,1}$,mm^3	$S_{y,2}$,mm^3	S_x, mm^3
Circle	117.8	117.8	33.65	-	33.65
Relo	122.54	122.54	39.19	28.73	33.15

There were two types of experiments.
2.1 Experiments for determination of the take-out force Pto

In that case wooden elements (beams) made out of dry coniferous wood with sizes (length x height x width): 150 mm x 60 mm x 48 mm. We drive in them nails of the two types so that the top of the nail comes out of the other side of the wooden element. After that the nail is taken-out. A mechanical testing machine Instron1195 was used, allowing to mark-down the diagram moving – force when we drive and take-out the nails. From these diagrams we calculate the maximum force of the driving in and the removal. We drilled, in advance, holes with 3 mm diameter in the wooden elements, to assure the driving was to be done easily, and without unnecessary force that would possibly lead to the deformation of the nails. There were 10 experiments held with each of the two types of nails.

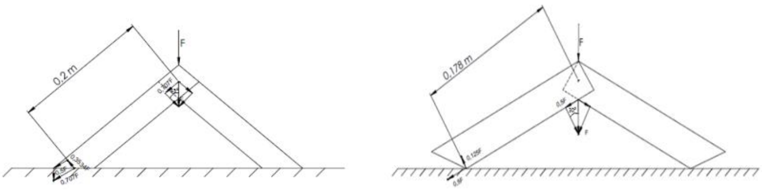
2.2 Experiments for determination of the torque Mr

In this case, wooden slats with dimensions (thickness x length x width) 30 mm x 200 mm x 65 mm from dry coniferous wood were used. Two slats are connected to each other with a nail at a 900 angle. The resulting wooden structure was tested in rotation under two types of load: when an external force acts simultaneously on the two slats - Fig. 4.; when an external force acts on only one slat - Fig. 5. The maximum moment at which the structure becomes inefficient (the slats are rotated relative to each other) is denoted with by and respectively. Using the calculation schemes for these moments shown in Fig. 3c and Fig. 4c is obtained:

$$M_r^{two} = 2 \times 0.2 \times 0.3543\,F \text{, Nm} \qquad (4)$$

$$M_r^{one} = 0.155F \text{, Nm}$$

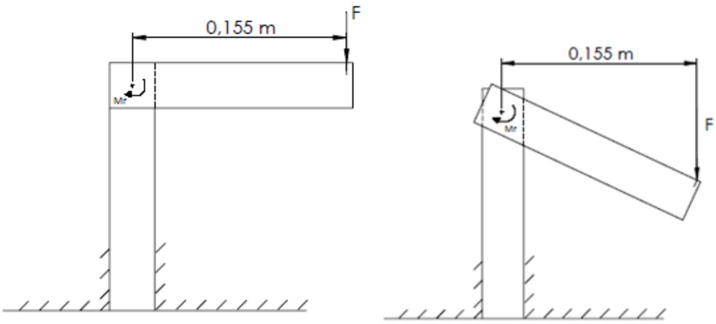
a) b)



c) d)

Fig.4. Pictures of tested wooden structure when force acts simultaneously onthe two slats: a – in the beginning; b – during the experiment; c, d – scheme to determine the moment

a) b)



c) d)

Fig.5. Pictures of tested wooden structure when force acts on one slat:
a – in the beginning; b – during the experiment;
c, d – scheme for determine of torque

III. Results

3.1 Determination of the driven and take-out forces

The driving of the nails is at a speed of 10 mm / min, and the removal of them is at a speed of 20 mm / min. The obtained values of the forces of driving Fd and take-out Fto are given in Table 2.

When connecting the wooden slats, the nails were driven in at a speed of 10 mm / min. The speed of movement of the contact element in the torque test Mr was 5 mm / min. The results are shown in Table 3. Due to the small differences in the values of the moments in the individual experiments, in Table 3 only their average values are given.

Table 3. Average values of M_r^{two} and M_r^{one}

Crosssection	M_r^{two}, Nm	M_r^{one}, Nm
Circle	20.83	7.6
Releaux Triangle	34.72	15.2

Table 2. Driven in and take-out forces

Type	Driven forceF_d, N	Take out force F_{to}, N
Circle cross-section	3728	2453
	3267	2158
	3482	1864
	3709	2394
	2943	2551
	3434	2048
	3744	2366
	3160	2370
	3460	2483
	3420	2644
Average	**3435**	**2333**
Relo Triangle cross-section	4513	5494
	4218	4513
	4120	5297
	4120	5240
	4120	4905
	4218	5248
	4194	4463
	4124	4562
	4158	4470
	4262	5274
Average	**4205**	**4947**

IV. CONCLUSION

From Table 1 it can be seen that the resistance against elastic bending of a nail with a section of the Reuleaux Triangle depends on the application point of the external force. Fig. 6 shows the forces F1, F2 and F3, which are used to determine the elastic section modulus S. The difference in the magnitude of these forces gives us grounds for the following conclusion:

When it is necessary to achieve maximum resistance against elastic bending of a nail with a Reuleaux Triangle section, when driving the nail it must be oriented so that the external force acts in the direction of the force F1 from Fig. 6.This means that, when using the new nail, an oriented driving can be performed according to the location of the edges on its stem. Oriented driving is a unique quality of the new nails, which will lead to drastic changes in the integration of wooden structures.

From Table 2. we can calculate the difference between the average forces of driving and removing a nail with a round section and with the Reuleaux Triangle one:

When driving a nail with a section of Relo's Triangle, the force $F_{d,R} = 1.24F_{d,C}$.

When removing a nail with a section of the Relo Triangle, the force $F_{to,R} = 2.12F_{to,C}$.

This means that wooden structures, whose elements are joined with nails with a Reuleaux Triangle section, will have twice as much resistance to destruction as those, joined with ordinary nails, when the wooden structures are subjected to superior destructive forces.This result can be explained by the following effects, which occur when driving and taking-out a nail with a Reuleaux Triangle section: (i) in the ends of the edges of the nail you get a compaction of the wooden material, which increases the coefficient of friction and the friction force in these areas along the length of the nail; (ii) the larger perimeter determines a larger area of the

surrounding surface of the nail body and hence a greater friction force on this surface than the friction force arising on the surrounding surface of a nail with circular section.
From Table 3. it can be determined:

When an external force acts simultaneously on two elements of a wooden structure, the maximum moment at which the elements will not rotate relative to each other is M_(r,R)^two = 1.66 M_(r,C)^two.When an external force acts on an element of a wooden structure, the maximum moment at which the elements will not rotate relative to each other is M_(r,R)^one = 2M_(r,C)^one.This means that wooden structures, which elements are connected with a nail with a Reuleaux Triangle section will have between 1.66 and 2 times more resistance to destruction than those, connected with ordinary nails, when forces, which strive to rotate the wooden elements relative to each other, act on them. This result is due to the presence of three longitudinal edges on the body of the nail with a Reuleaux Triangle section.

The presented results were obtained by using one nail of each type to connect the wooden elements. When using N number of nails, the effects of applying a nail with a section of the Relo Triangle will increase in proportion to N, when building wooden structures. In this way, greater resistance of wooden structures can be achieved, both in conditions of static external forces (furniture) and in dynamic forces (hurricanes, earthquakes, floods).

An important feature that can help the wide application of the new type of nails is that for its production the same materials, machines and technologies are used, which are used for the production of nails with round section.

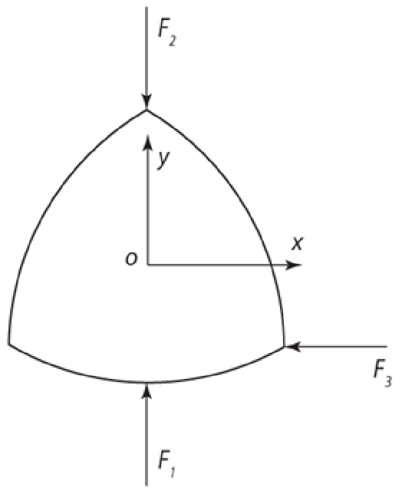


Fig. 6. A scheme of the forces, acting upon a section of a Reuleaux Triangle nail, when determining the elastic section modulus S: F1> F3> F2

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