

Frost Crack Impact on European Beech (*Fagus sylvatica* L.) Wood Quality

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Abstract

Frost crack represents one of the main defects which affect European beech wood quality. Therefore, the purpose of this paper is to improve the knowledge regarding both the impact of frost crack on European beech wood quality and the frost crack characteristics which affect wood quality. In order to do this, nineteen European beech trunks with frost crack have been studied. Each trunk has been cross-cut every 1 meter and the characteristics of frost crack and frost crack star-shaped heart have been measured in each cross-cut section. The defects which accompany frost crack have also been identified in each cross-cut section. Moreover, the possibility of determining these defects using the IML RESIF500 – S Resistograph has been tested. The research has emphasized the existence of statistical correlations between frost crack star-shaped heart expansion, frost crack rib prominence and frost crack length. These correlations are expressed by multiple linear regressions. The presence of defects which affect wood structure leading to a decrease in penetration resistance can be determined accurately with the resistograph. Decay (in frost cracks older than 8 years) and ring shake have been identified as the most frequent defects which accompany frost crack. The measurements made on the frost cracks studied have been gathered in a graph which shows frost crack impact on European beech wood quality. The results obtained lead to the improvement of the criteria of European beech wood quality assessment by expanding the already existent knowledge and by identifying new aspects which may complete standing wood quality determination and sorting methods.

Keywords: broadleaves, decay, frost-shrinkage, resistograph, ring shake, wood defects

Introduction

Frost crack is the radial crack developed along the trunk, sometimes with helix-like direction, caused by extremely low temperatures in winter time. It is more frequent in broadleaves than in conifers. Among broadleaves species affected by frost crack one could mention: Norway maple (Hart and Dennis, 1978), elm, poplar, walnut, beech, plane tree and chestnut (Franklin and Clatterbuck, 2004), silver birch (Kula *et al.*, 2006), and sugar maple (Burton *et al.*, 2008). Extreme frost causes frost cracks in all indigenous oak species (Haralamb, 1967). Turkey oak (*Q. cerris*) and Hungarian oak (*Q. frainetto*) are the most vulnerable species (Haralamb, 1967; Negulescu and Săvulescu, 1957; Stănescu, 1979; Stănescu *et al.*, 1997; Şofletea and Curtu, 2001, 2007). Sessile oak (*Q. petraea*) and common oak (*Q. robur*) are also affected by frost crack (Cinotti 1989, 1991; Savill and Kanowski, 1993), the former being more vulnerable to extreme frost than the latter (Haralamb, 1967; Negulescu and Săvulescu, 1957; Stănescu *et al.*, 1997; Şofletea and Curtu, 2001, 2007). Among conifers, firs resist to winter frosts well, and the frost crack only appears in the most sensitive species (*A. pinsapo*, *A. numidica* and *A. cephalonica*) at temperatures below -15°C (Aussenac, 2002). Also, frost crack affects *A. alba* (Dinulićă, 2007) and *A. concolor* (Wagener, 1970).

Kula *et al.* (2006) states that frost crack is formed when tree trunks freeze and temperature changes very suddenly. It appears under the form of longitudinal cracks situated towards the base of trunks in species with wide medullar radii. An important factor in frost cracks is represented by the water content of trees during winter, this being strongly related to the soil water content (Cinotti, 1989). Frost crack appears because of uneven tensions inside tree trunks caused by the different contraction of wood layers when temperature drops heavily and suddenly (Decei, 1975; Northover, 2006; Wagener, 1970). Frost cracks result from tension stress more in tangential than in the radial direction of wood's annual rings (Kubler, 1983, 1988; Parker, 1963; Wagener, 1970). When the volume of the outer layers decreases rather suddenly while the inner layers are still free from frost and have shrunk a little, differences in external tension will cause the outer layers to split vertically (Parker, 1963; Wagener, 1970). The main cause is frost-shrinkage due to freezing-out of cell moisture into lumens of wood cells. Other causes are the more rapid cooling of the trunk outer wood, expansion of freezing water in cell lumens, and formation of ice lenses in wood (Kubler, 1983, 1988). Frost cracks can be deep and can almost reach the centre of the trunk or can be shallow. Deep frost cracks stay on the trunk for the entire lifespan of the tree while the shallow ones can heal without leaving any mark on the tree trunk. Deep frost cracks do not heal because year by year, during

winter, they re-open being lines of minimum resistance (Decei, 1975; Northover, 2006). Shigo and Larson (1969) consider that frost cracks that have a rib on the external part are deep frost cracks which penetrate the trunk. Frost cracks that do not have a rib are most often shallow ones. These authors mention that a tree can be affected by more than one deep frost crack, in which case a star-shaped pattern appears in transversal section. This has been called frost crack star-shaped heart (Decei, 1975). The same authors state that, in all cases, frost cracks produce frost crack star-shaped heart. The presence of frost crack star-shaped heart downgrades round industrial wood to split wood. Frost crack may also be accompanied by ring shake as well as ingrown bark, the latter defect appearing if, after a certain period of time, the discontinuity has been covered by new tissues (Beldeanu, 2001).

The purpose of this paper is to emphasize the impact that frost crack has on European beech wood. The vulnerability of European beech to late frost and the frequency of frost crack in European beech tree stands of 14 up to 18% in the studied area (Câmpu and Dumitrache, 2013) are a justification of this research. The defect is important because of its frequency but mostly because of the impact that frost crack star-shaped heart has on wood quality. It can downgrade round industrial wood to firewood. Thus, frost crack is part of wood defects which are taken into consideration when establishing the quality class of standing trees (MAPP, 2000). European beech trees with frost crack can be downgraded by 2 or 3 quality classes (Câmpu, 2008; Câmpu *et al.* 2008). Decei (1975) considers that frost crack does reduce wood value as it is an area of penetration for micro-organisms that stain and cause the decaying of wood. At the same time, European beech is the most common broadleaves species, accounting for about 31% of Romania's national forests (MMP, 2010). From a total of 9,5 million m³ representing the volume of wood harvested in 2010 from state forests, about 3,3 million m³ is European beech wood. Moreover, from 2006 until 2012 European beech wood accounted for 30 to 35% of the wood harvested from national forests (MMS, 2013).

Materials and methods

Research places

The wood used for this research came from natural, harvestable European beech tree stands from the watershed of rivers Argeş and Târlung, Romania (Fig. 1). Both watersheds are situated in a mountainous area, at an altitude between 900 and 1200 m. In this area, European beech tree stands are located in wet and cold valleys with frost pockets which favour the occurrence of frost crack. Field work took place in the landing of felling areas where European beech tree trunks with frost crack could be found. In the spring of 2008 and 2009, the frost cracks from Târlung river watershed were analyzed followed in March 2014 by those from Argeş river watershed.

Field data collection and equipment

In all, nineteen European beech trunks with frost crack have been analysed – eleven in Târlung river watershed and eight in Argeş river watershed. These trunks were cross-cut at the length of 1 m resulting in 128 transversal sections. The main characteristics of frost crack and frost crack star-shaped heart were measured for each section according to the methodology established by Câmpu (2008; 2009). This methodology involves the following steps (Fig. 2):

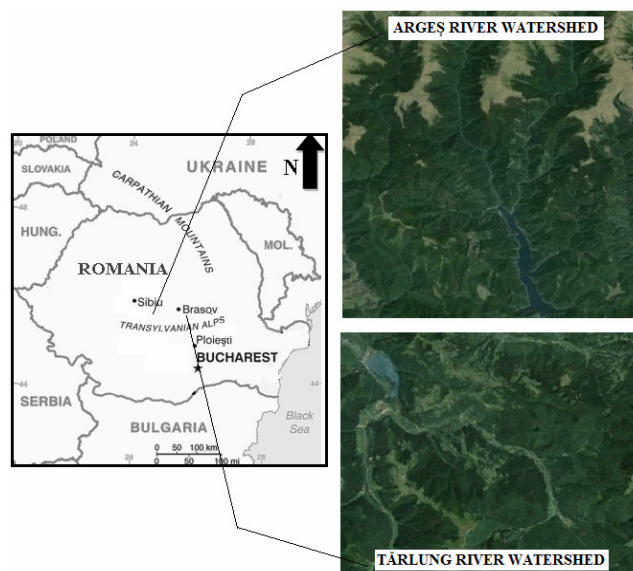


Fig. 1. The locations of study sites (Argeş and Târlung rivers watersheds)

- frost crack rib – its length (L) on the tree trunk as well as its maximum prominence (P_{max}) was determined;
- frost crack age (A) – this was determined by counting the annual rings from the frost crack rib, at the level of P_{max} (in the healing tissues annual rings are wide and they can be easily identified and counted by using a field magnifying glass);
- frost crack star-shaped heart – its expansion in transversal section (E) was determined, in the direction of maximum development, as a percentage of the section diameter, at the level of P_{max} ;
- the affected trunk length, located above the frost crack (L_a) – this was determined by cross-cutting the trunk every 1 meter above the place where the frost crack rib is no longer visible;
- the affected trunk length located below the frost crack (L_b) – this was determined by cross-cutting the trunk below the level where the frost crack rib is no longer visible.

Also, the trunk diameter (D) corresponding to P_{max} as well as the diameter of each section have been measured. The surface occupied by the frost crack stellar heart along with the surface of the trunk transversal section have been determined by digitization based on photographs of cross-cut sections. AutoCAD software has been used for digitization. The data gathered have been used for the graph in Fig. 5.

For each section, the internal defects which accompany frost crack were identified. Likewise, the possibility of determining the presence and size of internal defects using the IML RSIF500 – S Resistograph based on wood penetration resistance diagrams was studied (Fig. 3). The use of IML RESIF500 – S Resistograph represents a non-invasive method for analysing wood quality. The Resistograph may be valuable for studying wood characteristics among and within tree rings. This instrument has been designed to meet the special requirements of practical examination of standing trees, structural timbers, and poles (Isik and Li, 2003; Rinn *et al.*, 1996; Ukrainetz and O'Neill, 2010). The device uses a needle-like drill bit with a diameter between 1.5 and 3.0 mm powered by an electric motor with a rechargeable battery which can be replaced, thus offering portability and longer working time. It measures wood penetration resistance

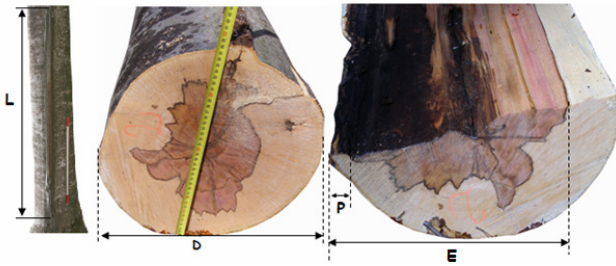


Fig. 2. Measurement of frost crack characteristics and of frost crack star-shaped heart (Câmpu, 2008; 2009): *L* – frost crack length; *D* – diameter of trunk transversal section; *P* – frost crack rib prominence; *E* – frost crack star-shaped heart expansion



Fig. 3. Use of IML RESIF500 – S Resistograph for identifying defects which accompany frost crack



Fig. 4. Frost crack star-shaped heart in transversal and longitudinal section

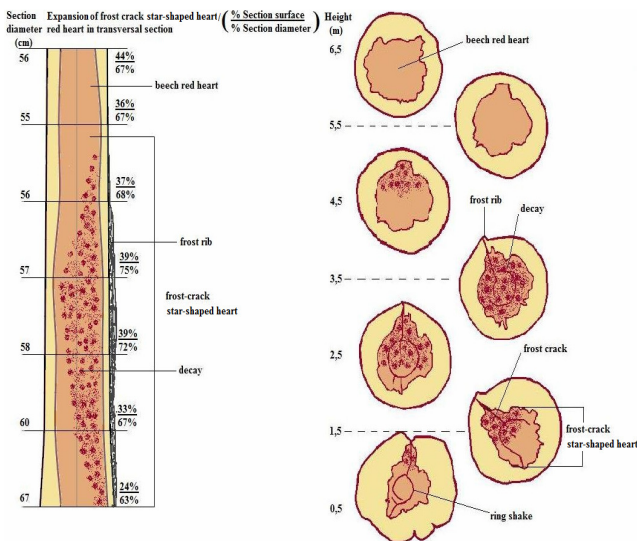


Fig. 5. Frost crack graphic pattern and impact on wood quality

corresponding to the depth of the hole. The drill bit moves forward by spinning at a constant speed through the entire hole depth. The torque needed for maintaining a steady penetration speed corresponds to wood resistance and it is registered on a diagram at its corresponding depth (Lear, 2005). The variation peaks on the diagram correspond to high resistance and density while low points on the diagram are associated with low resistance and density which may cause certain internal defects such as cavities, decay, areas with wood in different stages of decay and cracks (Kasal and Anthony, 2004).

Data analysis

The statistical analysis of data involved a first stage when the proportion occupied by frost crack star-shaped heart from the trunk cross-cut section diameter in the direction of its maximum development has been calculated. Likewise, the proportion occupied by frost crack star-shaped heart from the cross-cut section surface has been determined. The second stage involved the determination of the main statistical indicators of the variations of studied characteristics (mean, standard error, median, standard deviation, variation coefficient, minimum and maximum). Further on, the correlations between frost crack and frost crack star-shaped heart characteristics have been identified by using the multiple linear regressions. Thus, a linear model depending on *Pmax* and *L* has been created for the determination of frost crack star-shaped heart expansion. The regression significance has been tested with the Fisher test (*F*) while the significance of the independent variables coefficients *Pmax* and *L* has been tested using the *t* Student test for a transgression probability of 5%, 1% and 0,1%. The correlation intensity, expressed by the correlation coefficient has been estimated by using Roemer – Orphal’s scale (0.0-0.10, no correlation; 0.10-0.25, very weak; 0.25-0.40, weak; 0.40-0.50, moderate; 0.50-0.75, strong; 0.75-0.90, very strong; 0.90-1.0, full correlation).

Results and discussions

The analysis of the nineteen trunks led to the determination of the values for the main characteristics of frost crack and frost crack star-shaped heart (Table 1).

Based on the data from Table 1 the main statistical indicators of the variations of frost crack and frost crack star-shaped heart characteristics were determined (Table 2). Thus, it can be noticed that frost crack length displays the biggest variation. It is characterized by a variation coefficient of 60%. Câmpu (2008, 2009) shows that the most frequent frost cracks in tree stands are those with the length between 2 and 4 m (52%) followed by those with the length under 2 m (36%) and by those with the length over 4 m (12%). The expansion of frost crack star-shaped heart in radial section displayed the smallest variation coefficient of 16%.

Observations of practical importance were made regarding the main characteristics of frost crack and frost crack star-shaped heart. Thus, in most cases, the distance between the frost crack base and the tree base does not exceed the stump height (about 30 cm). When the distance between the frost crack base and the tree base exceeds the stump height, frost crack star-shaped heart develops below the frost crack at a distance of maximum 1 m. Regarding this, Decei (1975) states that frost crack star-shaped heart occurs only in the area where cracks appear. It develops below the frost crack on about 1 m only in isolated cases.

Table 1. Frost crack and frost crack star-shaped heart characteristics

No. of tree	<i>D</i>	<i>P max</i>	<i>A</i>	<i>L</i>	<i>E</i>	<i>La</i>	<i>Lb</i>	Other defects
-	[cm]	[cm]	[years]	[m]	[%D]	[m]	[m]	-
Târlung River Watershed								
1	40	4	8	3	60	1.7	-	Ring shake
2	32	5	16	2.6	58	2.1	1,0	Decay
3	60	4	10	5	67	2.5	-	Ring shake
4	46	3	8	2.2	42	1.5	0,7	Decay
5	52	3.5	10	2.5	54	1.8	-	Decay
6	36	2.5	6	1.7	42	1.0	-	-
7	44	5	10	2.1	54	1.8	-	Decay
8	66	7	15	2.5	65	2.5	-	Ring shake
9	54	4	12	2	55	2.0	0,5	Decay
10	70	6	15	3	70	2.4	-	Ring shake
11	48	3	8	1,7	45	1.4	-	Decay
Argeş River Watershed								
1	60	4	9	5	54	2.0	0,5	Ring shake
2	71	5	11	7.1	66	1.7	0,5	Decay
3	96	5.5	8	4.5	59	1.5	0,5	Ring shake
4	33	4	8	9.9	57	1.4	0,3	Ring shake
5	44	4	15	2.5	40	1.0	0,3	Decay
6	55	6	8	2	55	1.3	0,5	Ring shake
7	64	5	10	3	58	1.5	0,5	Ring shake
8	46	3	7	3,5	50	1.0	0,5	Decay

Note: *D* was measured at the level of *Pmax*

Table 2. Descriptive statistics of frost crack and frost crack star-shaped heart characteristics

Frost crack and frost crack star-shaped heart characteristics	Statistics					
	Mean \pm standard error	median	standard deviation	variation coefficient	minimum	maximum
L	3.46 \pm 0.48	2.60	2.09	60	1.70	9.90
Pmax	4.39 \pm 0.27	4.00	1.20	27	2.50	7.00
La	1.69 \pm 0.11	1.70	0.47	28	1.00	2.50
E	55.32 \pm 1.98	55.00	8.63	16	40	70

Table 3. Results of multiple linear regression analysis of frost crack star-shaped heart radial expansion in relation to frost crack length and frost crack rib maximum prominence

Variable	Coefficient	Standard Error	<i>t</i> Statistic	P - value
($R^2 = 0.597$; Standard Error 5.814; Degrees of freedom Regression 2, Residual 16; Significance $F < 0.001^{***}$)				
Constant	28.945	5.599	5.169	<0.001 ^{***}
L	1.470	0.656	2.240	0.040*
Pmax	4.842	1.146	4.225	<0.001 ^{***}

Note: Asterisks denote significant correlations, ^{***} P-value < 0.001; ^{**} 0.001 < P-value < 0.01; ^{*} 0.01 < P-value < 0.05

However, this research has emphasized the existence of frost crack star-shaped heart above cracks as well, on about 1 – 2.5 m (Table 1), where it gradually decreases in size and turns into red heart. The latter could also be caused by the penetration of oxygen through the frost crack (Sorz and Hietz, 2008; Wernsdörfer *et al.* 2005).

The prominence of the frost crack rib gets bigger as the frost crack gets older. During the healing process, cambium produces healing tissues with wide annual rings. In time these lead to the formation of a prominent rib along the trunk (Decei, 1975; Northover, 2006). This rib is important because the radial expansion of frost crack star-shaped heart depends on its maximum prominence (Decei 1975). Thus, in the technical

norms for the evaluation of wood volume for commercial purposes MAPP (2000) states that a prominence rib of 1.00 to 2.00 cm indicates a recent, closed frost crack where no frost crack star-shaped heart has developed wood quality being unaffected. When the prominence rib exceeds 2.00 cm there is always a corresponding open frost crack, with black sap leaks which has frost crack star-shaped heart. The research conducted emphasized a multiple linear correlation between *E*, *L* and *Pmax* ($F < 0.001$). According to Roemer – Orphal's scale, the results obtained show that there is a very strong correlation ($R = 0.773$) between *E*, *L* and *Pmax* (Table 3). It is noticed that *Pmax* (P-value < 0.001) as opposed to *L* (0.01 < P-value < 0.05) has the biggest influence on *E*.

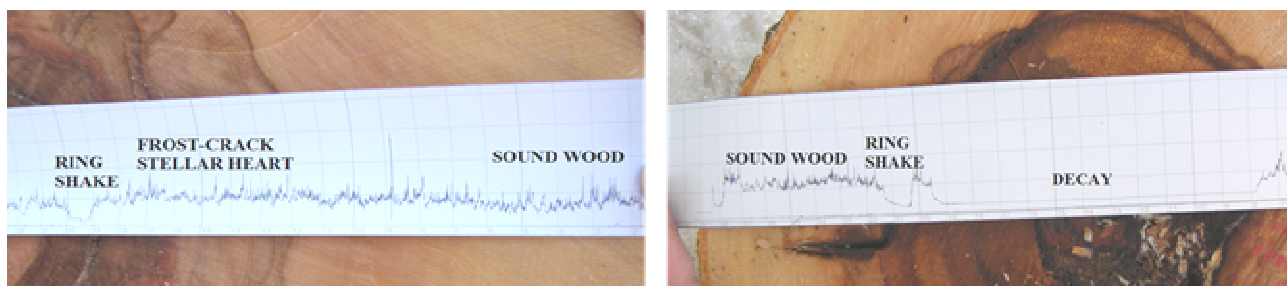


Fig. 6. Identification of internal defects (cracks and decay) on the diagrams extracted with IML RESIF500 – S Resistograph

In the case of frost cracks studied, the expansion of frost crack star-shaped heart varies between 40 and 70%, with a peak value at the level of the maximum prominence. In most cases the rib displays the maximum prominence at frost crack half length. Frost crack star-shaped heart is brown reddish with an uneven contour delineated by a dark brown line. In transversal section frost crack star-shaped heart is crossed by dark brown lines which suggest an evolution in stages (Fig. 4). This evolution is probably determined by the successive cracking and healing over the years.

The observations made on frost cracks and their characteristics in those 128 cross sections led to a graph which shows the way in which frost crack affects wood quality (Fig. 5). This graph shows that the ratio of the frost crack star-shaped heart surface to the cross-cut section surface is by 30 ... 40% smaller than the ratio of the diameter part occupied by frost crack star-shaped heart to the trunk diameter.

The defects which accompany frost crack most frequently are ring-shake and decay. Thus, in four of the nineteen trunks ring shake occurred (in frost cracks which were 8 years old or younger). Decay was noticed in five cases and both ring shake and decay were identified in six cases. In four cases wood quality is only affected by frost crack and frost crack star-shaped heart (in frost cracks ≤ 8 years). Decay occurs in all frost cracks older than 8 years, wood quality being strongly affected. In case a European beech tree is affected by more frost cracks, both frost crack star-shaped heart and decay expand faster than in the case of trees with a single frost crack and they can occupy the entire radial section. Câmpu (2009) mentions that about 9% of European beech trees with the diameter over 50 cm have two or even three frost cracks.

Internal defects which affect wood structure and penetration resistance can be accurately identified with the IML RESIF500 – S Resistograph. Thus, Fig. 6 shows specific diagrams of the Resistograph placed exactly on the section and direction from which they were extracted. The penetration resistance curve decreases reaching the lowest value where there is a crack in the wood or decay in different stages of development. No decrease of wood resistance was recorded in frost crack star-shaped heart; therefore, an estimate of its expansion in transversal section based on the diagrams is not possible. The variation of penetration resistance in this case can be compared with that of sound wood. Ukrainetz and O'Neill (2010) state that the diagrams obtained with the resistograph can be affected by errors caused by operator's movement, air temperature and proximity of knots. As a result, measurements must be taken when the air temperature is above the freezing point, in places away from knots and without the operator moving during the drilling. All these requirements have been met by the authors during this research.

Conclusions

Frost crack affects wood quality both by the expansion of frost crack star-shaped heart and by the fact that it is a gateway for wood xilophagous fungi. In time, these fungi lead to wood decay. The results showed that frost crack star-shaped heart expansion is positively correlated with frost crack length ($0.01 < P\text{-value} < 0.05$) and with the maximum rib prominence ($P\text{-value} < 0.001$). Thus, multiple linear regressions ($F < 0.001$) are used for the determination of the maximum expansion of frost crack star-shaped heart, expressed in percentages of the section diameter. Results have shown that frost crack star-shaped heart can be longer than frost crack by up to 1m in the lower part and by up to 1...2.5 m in the upper part. Similarly, the graph illustrates how frost crack star-shaped heart turns into European beech red heart in the upper part.

As far as the defects that accompany frost crack are concerned, it has been noticed that decay and ring-shake are the most frequent. Decay occurs in all frost cracks over 8 years old. Decay, ring-shake as well as other cracks, can be identified precisely with the resistograph based on penetration resistance diagrams. No decrease in wood penetration resistance is registered in the case of frost crack star-shaped heart. Therefore, the estimate of its expansion in transversal section based on the diagrams is impossible. Here the variation of penetration resistance can be compared with that of sound wood.

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