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Mehano-sorptivni učinek v lesu
Mechano-sorptive Effect in Wood

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Mehano-sorptivni učinek (MSU) uvrščamo med zelo zanimive, vendar še slabo pojasnjene pojave pri obnašanju lesa. Zato smo se pri naši raziskavi odločili, da zanj poiščemo najbolj značilne vzroke, nato pa skušamo ugotoviti, kateri so bistveni mehanizmi tega pojava in na katerem nivoju lesne sestave pretežno delujejo. Z natančnimi meritvami majhnih, čistih, upogibnih vzorcev smrekovega lesa različnih kategorij (mladega, zrelega, kompresijskega) v natančno določeni spremenljivi klimi ter nato še z meritvami vlažnostnih gradientov v prerezu vzorcev smo ugotovili mogoče vzroke, ki povzročajo mehano-sorptivni pojav. Bistveni povzročitelj je vlažnostni gradient, ki povzroča prehodne sorptivne napetosti. Dokazali smo tudi, da ima pri tem pojavu velik vpliv sestava celične stene oziroma kot vitja mikrofibrilov.

Ključne besede: obnašanje lesa, mehano-sorptivni učinek, les zreli, les mladi, les kompresijski

The mechano-sorptive effect (MSE) can be classified as a very interesting, but not yet completely explained phenomenon in wood behaviour. In our research we therefore decided to find its most relevant mechanisms and then to try to find out at which level of the wood structure they operate. By very accurate measurements of deflections on small, clear bending specimens of spruce wood (juvenile, adult and compression wood) in changeable climate conditions, and additionally by measuring the intensity of moisture content in the cross section, we found some possible reasons for MSE. The decisive factor could be the gradient of moisture content with resulting sorptive stresses; on the other hand, the cell wall structure or more precisely the microfibrile angle probably has an important role as well.

Keywords: wood behaviour, mechano-sorption, adult wood, juvenile wood, compression wood

0 UVOD

Les uvrščamo med značilne viskoelastične materiale. Njegove časovno spremenljive deformacije postanejo izredno zanimive ob sočasnem delovanju mehanskih obremenitev in spremenljive vlažnosti. Ta pojav, v literaturi imenovan kot mehano-sorptivni učinek (MSU) [1] in [2], je cilj številnih raziskav, ki analizirajo lezenje lesa v okolju s spremenljivo vlažnostjo [3] in [4]. Za njegovo analizo je treba poznati vzroke, nato pa določiti ustrezne mehanizme, ki omogočajo pri tem pojavu tako nenavadne odzive.

Danes poznamo pri razlagi MSU dve nabolj popularni hipotezi:

- po prvi [5] in [6], se skuša vse deformacije, ki se pojavijo med MSU, umestiti na molekularnem nivoju po Eyringovi teoriji molekularne kinetike,
- po drugi [7], se seli vse mehanizme MSU na nivo sestave celične stene, kjer naj bi nastanek "drsnih ravnin" v tlačnih conah zaradi trajnih sprememb tkiva povzročal vrsto značilnih pojavov.

Ker je MSU zelo zapleten pojav, smo se v naši raziskavi odločili, da najprej poiščemo bistvene vplive, nato pa skušamo še ugotoviti, na katerem nivoju sestave lesnega tkiva se pri MSU največ dogaja. Zato smo naredili omejeno izbiro.

0 INTRODUCTION

Wood can be classified as one of the typical viscoelastic materials. It is very interesting to follow its deformations during the simultaneous action of mechanical stresses and changeable humidity, which are much greater than at constant climate conditions, and to great extent recoverable. This phenomenon, the so called mechano-sorptive effect (MSE) [1] and [2], is the primary goal of numerous investigations, analysing the sorptive creep in a changeable climate [3] and [4]. To be able to analyse MSE it is important first to establish the deciding factors, which cause it and then find the appropriate explanation for such interesting reactions.

Nowadays we can find two popular hypotheses explaining MSE:

- the first one [5] and [6], tries to interpret all the deformations occurring during MSE experiments on the molecular level according to Eyring's molecular kinetics theory,
- the second one [7], considers the formation of slip planes in the compression zone, which takes place in the cell wall structure, as the main cause of most of the MSE phenomena.

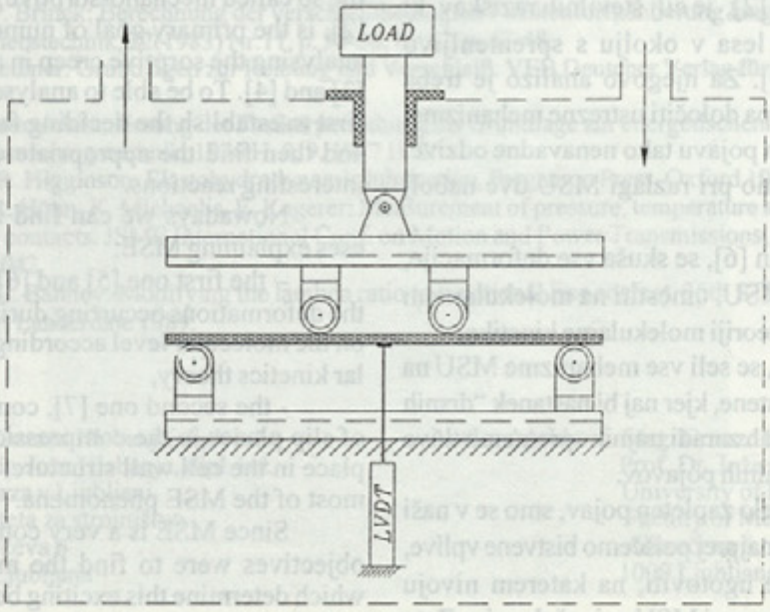
Since MSE is a very complex behaviour, our objectives were to find the most relevant factors which determine this exciting behaviour of wood and to find out at which level of the wood structure they are prevailing. Therefore we decided to:

1) Izbrali smo majhne, čiste vzorce značilnega lesa iste vrste. Na ta način smo izločili vpliv rasti, usmerjenost tkiva in vpliv grč. Majhni prerezi vzorcev so primerni pri analizi sorptivnih napetosti, ker se zaradi velikega razmerja vlagi izpostavljene površine in prostornine pojavijo že v zelo kratkem času znatni vlažnostni gradienti.
2) Odločili smo se za preiskavo vzorcev v majhni merilni celici, kjer lahko dalj časa vzdržujemo konstantno in homogeno klimo, natančno določene vlažnosti.
3) Določili smo natančno meritev v krajših časovnih intervalih z izločitvijo vlažnostnih deformacij.
4) Odločili smo se tudi za meritev vlažnostnih gradientov po prerezu vzorca v odvisnosti od časa ter nato še za izračun velikosti sorptivnih napetosti po metodi končnih elementov.
5) Izbrali smo tri različne kategorije lesa domače smreke (Picea abies, Mill.): mladega, zrelega in kompresijskega. Zaradi njihove specifične anatomske in kemijske sestave lahko primerjalno iščemo vpliv mikrofibrilnega kota na mehano-sorptivno obnašanje.

Na Lesarskem oddelku Biotehniške fakultete Univerze v Ljubljani je bila načrtovana in izdelana izvirna merilna veriga. Celico s prostornino 20 litrov je izmenično napajal zrak iz komore s solno kopeljo $MgCl_2$, ki je zagotavljala 33-odstotno relativno vlažnost, oziroma iz komore z vodno kopeljo s 95-odstotno relativno vlažnostjo. Upogibni vzorčki so merili: 5 ×10 × 200 mm. Merilnik dolžin (LVDT) je razbiral upogibke na sredini polja s konstantnim upogibnim momentom na spodnji strani vzorca zaradi eliminacije nabrekanja po višini. Obremenitve vzorcev so bile 10% oziroma 30% porušne trdnosti suhih vzorcev. Cikel vlažnostnih sprememb je trajal dva dni.

1) Take small, clear specimens of characteristic wood. Thus we eliminated the influence of growth, knots and cracks. Small specimens are specially suitable for the analysis of sorptive stresses. We can find strong gradients of moisture content (MC) in them because of the great ratio between the surface and the volume;
2) Investigate the samples in a small chamber, where a homogeneous and very precisely conditioned air humidity could be maintained;
3) Take short intervals between the measurements with accurate devices located in such places where we can avoid the dimensional changes during swelling and shrinkage;
4) Measure the time dependent intensity of MC in cross-section to estimate the intensity of sorptive stresses;
5) Select three different categories of wood - juvenile, adult and compression spruce wood (Picea abies, Mill.) The MS behaviour in various categories of wood might be quite different due to the substantial differences in their anatomical characteristics, microstructure and chemical composition.

The experimental set was designed and built at the Laboratory of the Department of Wood Science & Technology, University of Ljubljana. The reasonably small chamber was serially tube connected either with a salt bath ($MgCl_2$), which maintains very precise climate of 33%, RH or with a water bath that produces a 95% RH. The deflection was measured on bending loaded samples of 5 × 10 × 20 mm . The point of measurement was located at the bottom surface, in the attempt to avoid the dimensional changes during swelling and shrinkage. The specimens were loaded to an edge stress level of 10% and 30% of bending strength of the dry specimen. The duration of the humidity cycle was two days.



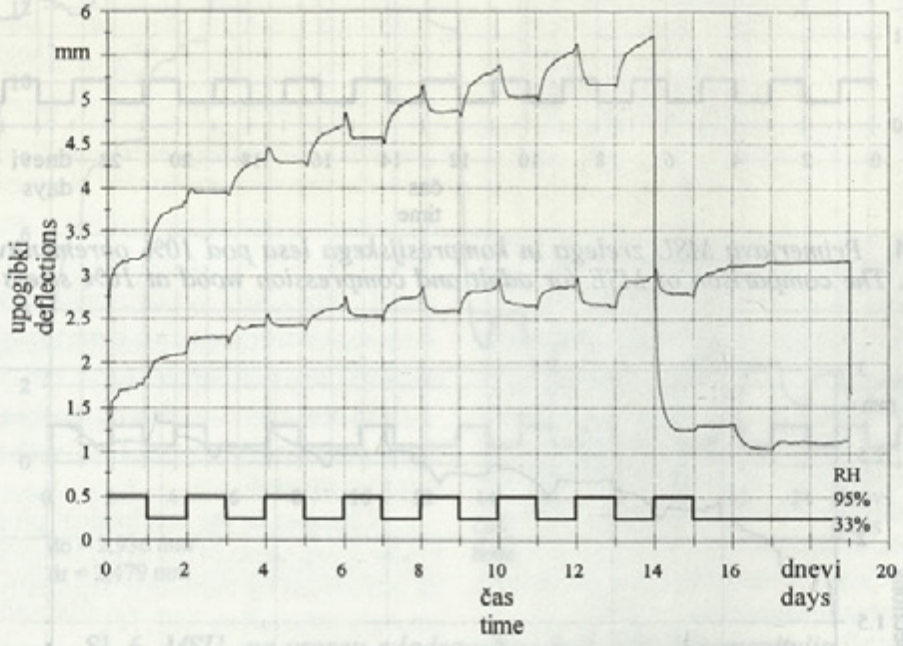
Sl.1. *Merilna naprava*
Fig. 1. *Experimental apparatus*

1 REZULTATI

Rezultati meritev zrelih vzorcev so izvrstno potrdili nenavadno obnašanje lesa pri MSU. Slika 2 prikazuje potek deformacij dveh zrelih vzorcev pod različnima obremenitvama. Občudujemo lahko skoraj idealno krivuljo mehano-sorptivnega lezenja. Zelo značilnemu velikemu prirastku deformacij med prvim vlaženjem sledijo manjši prirastki med vsemi naslednjimi sušenji. Opazno pa je tudi zmanjšanje povesov v vseh kasnejših intervalih vlaženja, kar je ena od značilnosti MSU. Ob razbremenitvi je bil elastični povratek nekoliko večji od začetnega (razlika je 18%). To pomeni ustrezno zmanjšanje modula elastičnosti in pomeni, da je v lesni zgradbi prišlo do nekaterih nepovratnih sprememb.

1 RESULTS

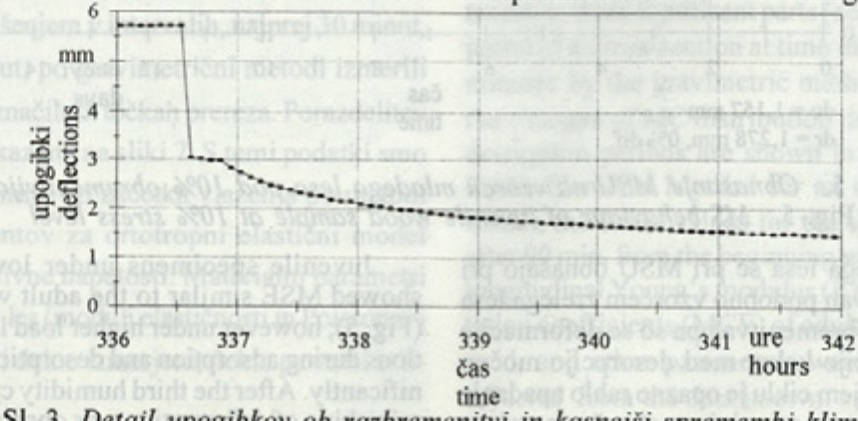
The results for adult wood specimens excellently confirmed the anomalous creep behaviour of wood called MSE. Figure 2. shows a comparison of adult wood specimens at two different stress levels. One can admire the quite ideal MS curve, with a relatively strong increase of creep deformations, which was expected due to high stresses. The most significant creep deflection increase occurs during the first wetting period, followed by smaller ones during all subsequent drying periods. The exciting and characteristic decrease of deformation in further wetting periods is evident. After unloading, the elastic recovery was somewhat greater (about 18%) in comparison to the initial elastic deformation, which means that the modulus of elasticity has decreased, and we are able to conclude that some irreversible changes in wood structure have occurred.



Sl. 2. *MSU zrelih vzorcev pod obremenitvijo 10% oz. 30% upogibne trdnosti*
Fig. 2. *The MSE of two adult wood specimens at 0.1 and 0.3 stress levels*

Na sliki 3 vidimo manjši izrez slike 2, ki prikazuje podrobnosti meritev ob razbremenitvi. Opazimo lahko tudi takojšen odziv vzorca ob spremembi klime.

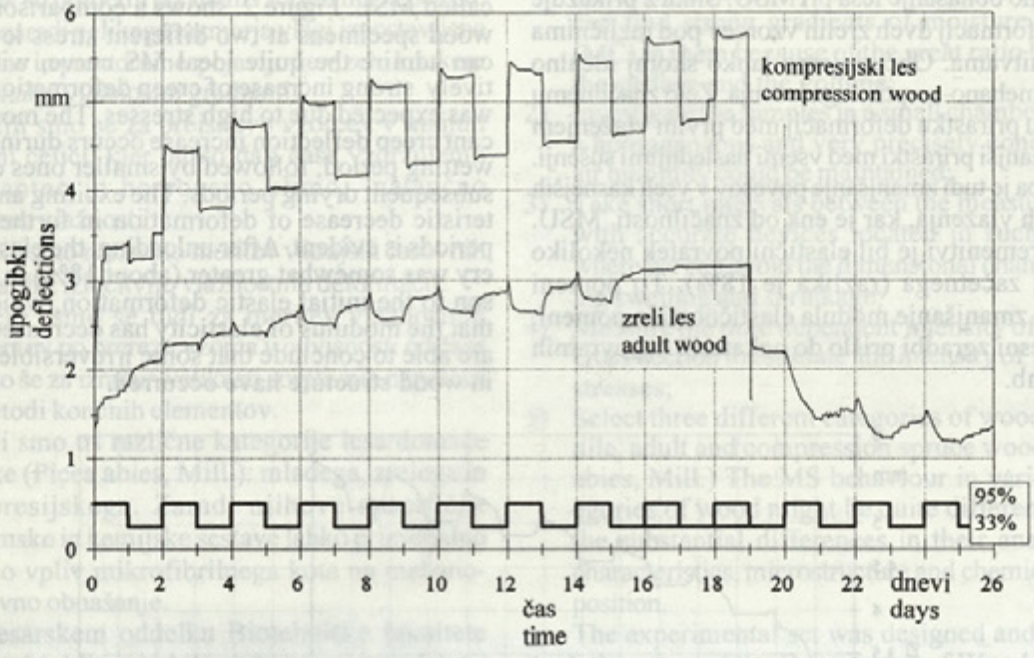
In the figure 3 we took an even smaller cut from figure 2, so that distinct measurements at the unloading are shown. We can see an interesting reaction of the specimen to the climate change.



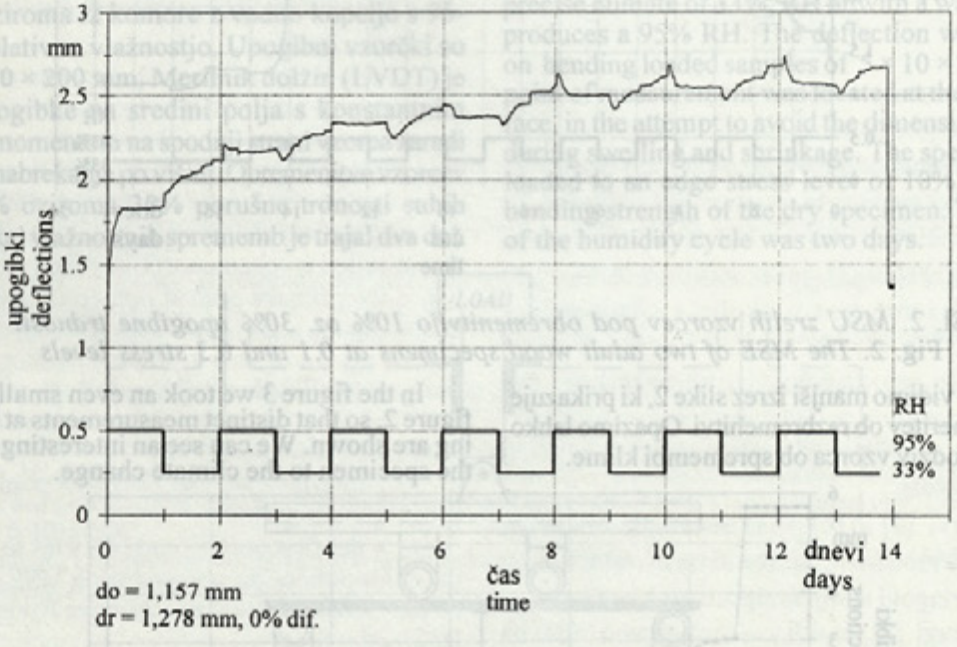
Sl. 3. *Detajl upogibkov ob razbremenitvi in kasnejši spremembi klime*
Fig. 3. *The detail at unloading before a climate change*

Primerjava MSU na vzorcih zrelega in kompresijskega lesa kaže zelo različno obnašanje ob vseh klimatskih spremembah.

The comparison of MSE on adult and compression wood specimens reveals a significantly different behaviour.



Sl. 4. *Primerjava MSU zrelega in kompresijskega lesa pod 10% obremenitvijo*
Fig. 4. *The comparison of MSE for adult and compression wood at 10% stress level*



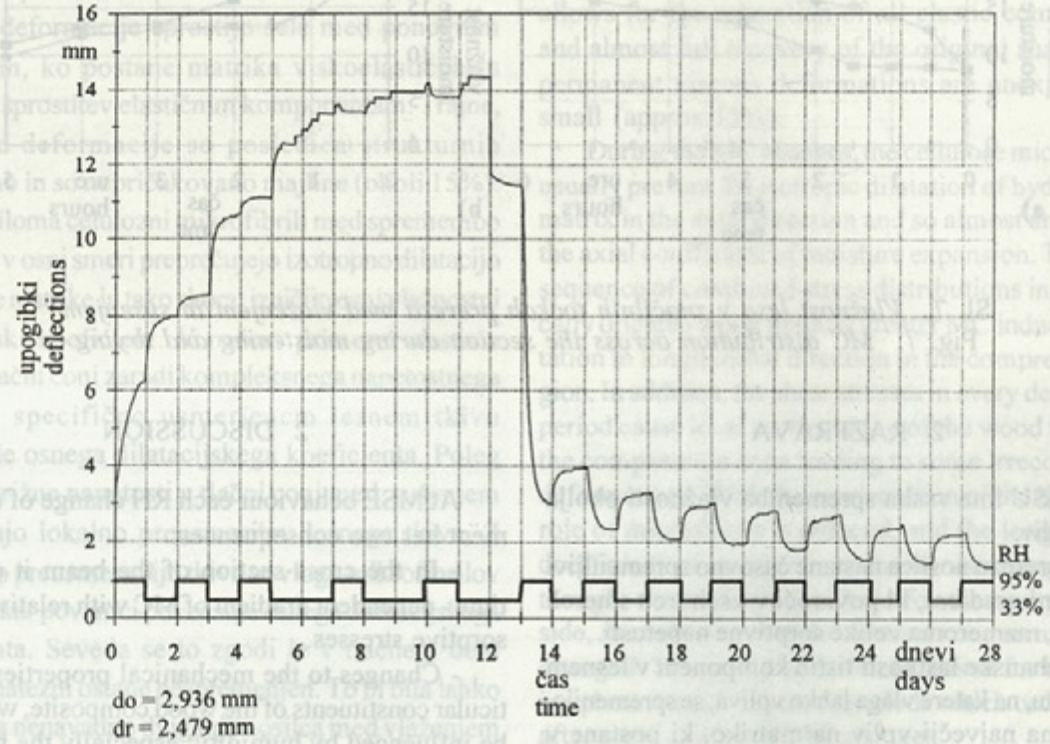
Sl. 5. *Obnašanje MSU na vzorcu mladega lesa pod 10% obremenitvijo*
Fig. 5. *MS behaviour of juvenile wood sample at 10% stress level*

Vzorci mladega lesa se pri MSU obnašajo pri nizkih obremenitvah podobno vzorcem zrelega lesa (sl. 5). Pri višjih obremenitvah pa so se deformacije tako med adsorpcijo kakor med desorpcijo močno zvečevale. Po tretjem ciklu je opazno rahlo upadanje med vlaženjem, kar nas spominja na obnašanje zrelega lesa.

Juvenile specimens under low stress levels showed MSE similar to the adult wood behaviour (Fig. 5); however under higher load level, the deflections during adsorption and desorption increased significantly. After the third humidity cycle, a slight diminishing of deformation was observed, resembling the adult wood behaviour.

Čeprav so upogibki po petih ciklih dosegli kar šestkratno vrednost začetnih elastičnih deformacij, so le-ti kasneje skoraj v celoti izginili. Med prvim vlaženjem po razbremenitvi je kar 80% v mehano-sorptivnih ciklih nabranih deformacij izginilo. To je morda najbolj osupljiv pojav MSU, ker kaže, da je delež trajnih, viskoznih deformacij glede na velikost upogibkov nosilca precej manjši od pričakovanega.

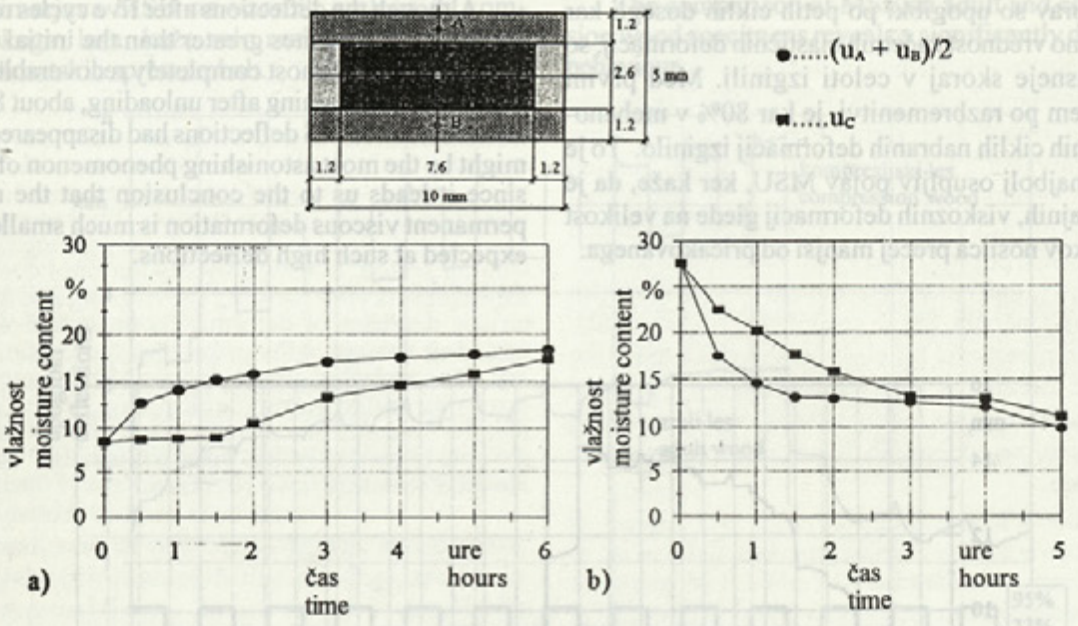
Although the deflections after five cycles reached a value even six times greater than the initial elastic ones, they were almost completely recoverable. During the first moistening after unloading, about 80% of all accumulated MS deflections had disappeared. This might be the most astonishing phenomenon of MSE, since it leads us to the conclusion that the role of permanent viscous deformation is much smaller than expected at such high deflections.



Sl. 6. *MSU na vzorcu mladega lesa pod 30% obremenitvijo*
Fig. 6. *The MS behaviour of typical juvenile wood at 30% stress level*

Da bi čimbolj natančno ugotovili, kako se sčasoma spreminja vlažnost lesa po prerezu vzorca, smo med vlaženjem in sušenjem v intervalih, najprej 30 minut, nato pa 60 minut, po gravimetrični metodi izmerili vlažnost v treh značilnih točkah prereza. Porazdelitev vlažnosti je prikazana na sliki 7. S temi podatki smo nato za čas 90 min. od začetka vlaženja po metodi končnih elementov za ortotropni elastični model izračunali sorptivne napetosti. Materialni parametri za zrel smrekov les (moduli elastičnosti in Poissonovi količniki) so bili delno izmerjeni, delno pa vzeti iz literature.

In order to estimate the magnitude of sorptive stresses we have measured the moisture content intensity in three significant parts (central and both edge parts) of a cross-section at time intervals of 30 or 60 minutes by the gravimetric method. The results of the changes of MC distribution during sorption and desorption periods are shown in Fig. 7. Using the Finite Elements Method for an orthotropic elastic model, the stress values for the critical MC profile after 90 min. from the beginning were evaluated. The longitudinal Young's modulus (E) and moisture dilatation coefficients (MCE) of adult wood were measured, and other parameters were correspondingly adjusted from the data known.



Sl. 7. *Vlažnost lesa v značilnih točkah prereza med vlaženjem in sušenjem*
Fig. 7. *MC distribution across the section during moistening and drying*

2 RAZPRAVA

V MSU ima vsaka sprememba vlažnosti okolja dvojni vpliv:

- V prerezu nosilca nastane časovno spremenljivi vlažnostni gradient, ki povzroči v vseh treh smereh ustrezne, razmeroma velike sorptivne napetosti.
- Mehanske lastnosti tistih komponent v lesnem kompozitu, na katere vlaga lahko vpliva, se spremenijo. Vlaga ima največji vpliv na matriko, ki postane v vlažnem stanju izrazito viskoelastična [8].

Rezultati, dobljeni pri meritvah vlažnostnih gradientov na posebnih vzorcih, dokazujejo, da je osnovno gibalo obnašanja MS kombinacija stalnih, upogibnih napetosti in prehodnih vlažnostnih napetosti, ki dosegajo svoje ekstremne vrednosti približno po dveh urah, nato pa v naslednjih nekaj urah izginejo. Poleg tega pa so naše meritve deformacij pokazale, da se pojavi večina MS upogibnih prirastkov prav v času delovanja sorptivnih napetosti, tj. v intervalu šestih ur.

Vsaka sprememba vlažnosti lesnega tkiva povzroči prostorsko stanje sorptivnih napetosti, katerih predznak je odvisen od načina spremembe vlažnosti, njihova velikost pa od vlažnostnega gradienta in togosti materiala. Ker je E suhega lesa večji kakor E vlažnega, so tudi sorptivne napetosti med vlaženjem intenzivnejše. Tako dobimo med vlaženjem pod površino začasne tlačne sorptivne napetosti, med sušenjem pa natezne sorptivne napetosti, ki se superponirajo konstantnim upogibnim napetostim.

2 DISCUSSION

At MSE behaviour each RH change of environment has two consequences:

- In the cross section of the beam it causes a time - dependent gradient of MC with relatively high sorptive stresses.
- Changes to the mechanical properties of particular constituents of the wood composite, which can be influenced by humidity; especially the matrix is strongly affected by MC, [8].

The results, calculated on the basis of our measurements of MC gradients on dummy samples, show that the main reason for MS behaviour is a combination of permanent bending stresses and temporary sorptive stresses reaching their peaks after approximately two hours. Furthermore, our measurements of deflections showed that the majority of MS deformation increments develop during the action of sorptive stresses - that is, during the first six hours.

Each humidity change in the wood tissue causes a 3D state of sorptive stresses. Their sign depends merely on the kind of MC change (adsorption-desorption), while their intensity is defined by MC gradient and the stiffness of the material. Since E of dry wood is greater than E of wet wood, the sorptive stresses in sorption are greater than in the desorption period. Thus we get temporary compression sorptive stresses under the surface at desorption, and tension sorptive stresses at the adsorption period.

Tlačne napetosti prenaša pretežno matrika in v prvi fazi sušenja je ta vlažna in zaradi svoje viskoelastičnosti popušča ter predaja del obremenitve elastičnim komponentam. Na koncu faze sušenja matrika otrdi in zadrži novo obliko. Tako se v vsakem ciklu nabirajo deformacije .

Ob razbremenitvi suhega vzorca zadržuje matrika prej nabrane deformacije v notranjem ravnotežju in preprečuje elastičnim komponentam vrnitev v prvotno obliko. Tako se med cikli MS nabrane deformacije sprostijo šele med ponovnim vlaženjem, ko postane matrika viskoelastična in omogoči sprostitev elastičnim komponentam. Trajne, viskozne deformacije so posledica strukturnih sprememb in so nepričakovano majhne (okoli 15%).

Praviloma celulozni mikrofibrili med spremembo vlažnosti v osni smeri preprečujejo izotropno dilatacijo higrofilne matrike in tako skoraj izničijo osni vlažnostni dilatacijski koeficient. V našem primeru nastane samo v tlačni coni zaradi kompleksnega napetostnega stanja v specifično usmerjenem lesnem tkivu povečanje osnega dilatacijskega koeficienta. Poleg tega še strižne napetosti v tlačni coni med sušenjem povzročajo lokalno preusmeritev lesnega tkiva. Z omenjeno preusmeritvijo tkiva se vloga mikrofibrilov zmanjša, kar povzroči povečanje osnega dilatacijskega koeficienta. Seveda se to zgodi le v tlačnem delu prereza, natezni ostane nespremenjen. To bi bila lahko razlaga za nenavadno dviganje nosilca med vlaženjem po nekaj začetnih ciklih.

Vse navedeno velja za kompozite, ki imajo usmerjenost vlaken pretežno v osni smeri. Normalni, zreli les ima majhen mikrofibrilni kot in zato imajo celulozni mikrofibrili razmeroma velik vpliv. Nasprotno pa imajo mikrofibrili v kompresijskem lesu precej večji kot (30° do 45°), tako da postane vpliv kakršnekoli preusmeritev tkiva nebistven. Poleg tega je v tako usmerjenem kompozitu delež higrofilne matrike v velikosti modula elastičnosti pri tlaku in nategu v aksialni smeri odločilen.

Velik vpliv sorptivnih napetosti sta potrdila dva vzorca kompresijskega lesa, pri katerih med fazo sušenja ni bilo prirastkov deformacij. Kasnejša kontrola je pokazala, da imata vzorca drobne navpične razpoke, ki so nastale v času rasti in so sproščale dilatacije ter tako preprečevale nastanek nateznih sorptivnih napetosti v prečni smeri (sl. 8).

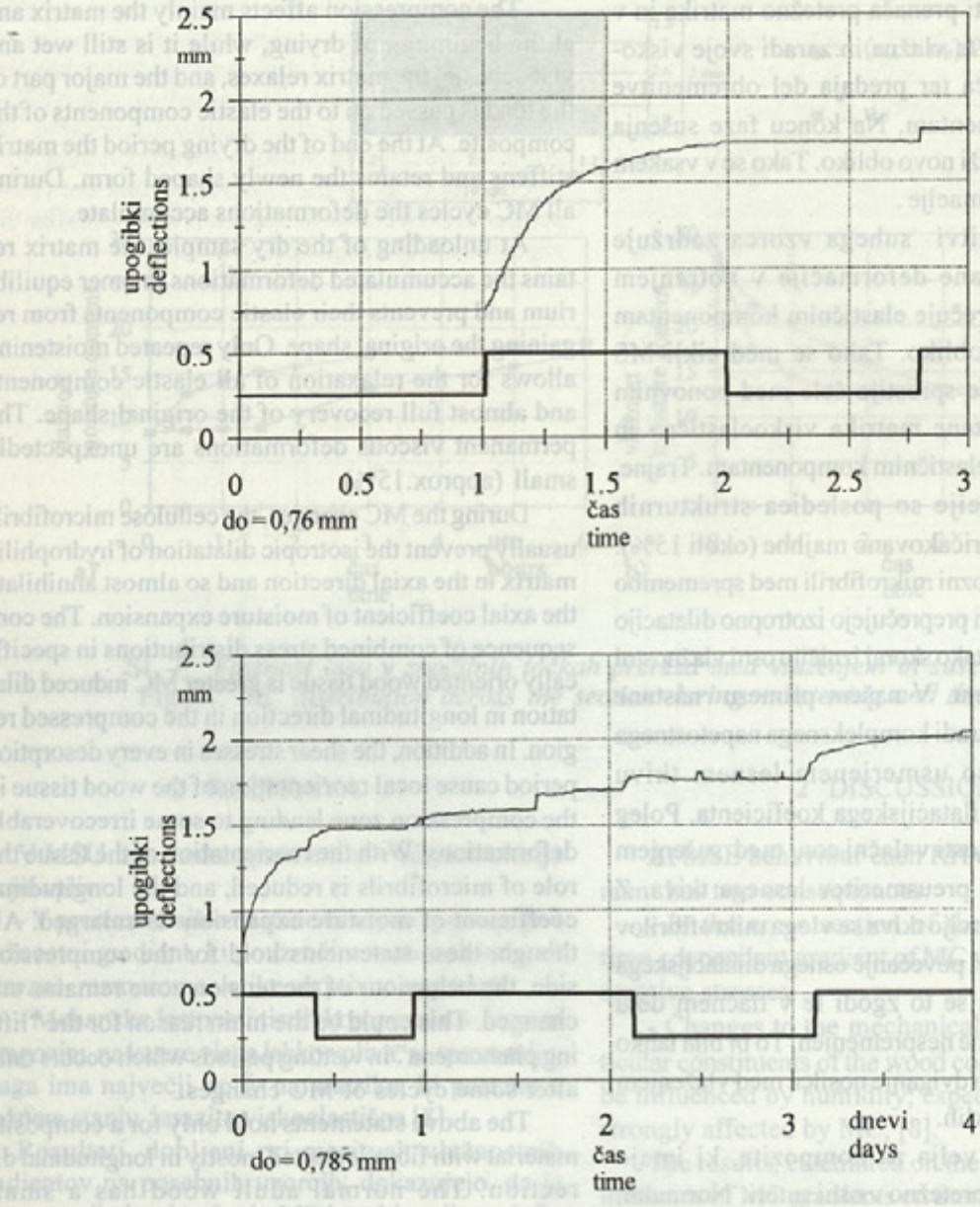
The compression affects mainly the matrix and at the beginning of drying, while it is still wet and viscoelastic, the matrix relaxes, and the major part of the load is passed on to the elastic components of the composite. At the end of the drying period the matrix stiffens and retains the newly shaped form. During all MC cycles the deformations accumulate.

At unloading of the dry sample, the matrix retains the accumulated deformations in inner equilibrium and prevents their elastic components from regaining the original shape. Only repeated moistening allows for the relaxation of all elastic components and almost full recovery of the original shape. The permanent viscous deformations are unexpectedly small (approx.15%).

During the MC changes, the cellulose microfibrils usually prevent the isotropic dilatation of hydrophilic matrix in the axial direction and so almost annihilate the axial coefficient of moisture expansion. The consequence of combined stress distributions in specifically oriented wood tissue is greater MC induced dilatation in longitudinal direction in the compressed region. In addition, the shear stresses in every desorption period cause local reorientation of the wood tissue in the compression zone leading to some irrecoverable deformations. With the reorientation of the tissue the role of microfibrils is reduced, and the longitudinal coefficient of moisture expansion is enlarged. Although, these statements hold for the compression side, the behaviour of the tension zone remains unchanged. This could be the main reason for the "lifting phenomena" in wetting periods which occurs only after some cycles of MC changes.

The above statements hold only for a composite material with fibres oriented mostly in longitudinal direction. The normal adult wood has a small microfibrile angle and consequently the cellulose microfibrils have relatively the greatest influence. By contrast, the microfibrils' angle in compression wood is much greater than in adult wood (30° to 45°), and the changes due to the reorientation of tissue become meaningless. Because of the characteristic orientation of microfibrils the moisture sensitive matrix becomes significant to the modulus of elasticity in longitudinal direction both at tension and at compression.

The great importance of sorptive stresses has been proved by some specimens of compression wood in which we did not find any increase of deflections in the desorption periods. The later inspection of these samples showed small vertical growth cracks, which enable tension sorptive stresses to develop during the desorption periods (Fig. 8.)



Sl. 8. *Vzorca kompresijskega lesa z navpičnimi razpokami pod 10-odstotno obremenitvijo*
Fig. 8. *Two samples of compression wood with cracks under 10% stress level*

3 SKLEPI

Na podlagi meritev in opravljene analize lahko sklenemo, da ima odločilno vlogo v MSU sočasno delovanje konstantnih upogibnih in vlažnostnih napetosti, ki so vse približno enake velikosti. Natančne meritve so pokazale, da so bistvene spremembe deformacij nastale v času delovanja sorptivnih napetosti in se je glavnina deformacij nabrala v šestih urah. Ko se je vlažnostni gradient zmanjšal in so vlažnostne napetosti izginile, so deformacije ostale skoraj nespremenjene.

3 CONCLUSIONS

It is evident that the synchronous action of constant bending stresses and sorption stresses has the key role in MSE. Both stresses were approximately of the same magnitude. The precise measurements showed that practically all the changes of deflections occurred while the sorptive stresses were present, and that most of the deformation increments occurred in a time interval of six hours. When the MC gradient diminished and sorptive stresses disappeared, the deflections remained practically constant.

V naši raziskavi smo ugotovili nekaj vzrokov in mogočih razlag mehano-sorptivnega obnašanja.

- Potrdili smo vse pojave MSU pri normalnem zrelem lesu.

- Ugotovili smo, da je glavni vzrok MSU sočasno delovanje stalnih upogibnih napetosti in kratkotrajnih časovno odvisnih sorptivnih napetosti.

- Predpostavljamo, da je vzrok dviganja nosilca zrelega in mladega lesa med vlaženjem povečan osni dilatacijski koeficient v tlačni coni prereza zaradi specifičnih napetosti v specifično usmerjenem lesnem tkivu.

- S primerjavo obnašanja MS v zrelem in kompresijskem lesu smo potrdili hipotezo, da je sestava celične stene zelo pomemben dejavnik pri MSU. Stisnjen les kaže viskoelastično lezenje brez značilnosti MSU, kar smo zaradi njegove posebne sestave celične stene pričakovali.

- Ugotovili smo tudi, da so med MSU nakopičene izredno velike deformacije po razbremenitvi ob ponovnem vlaženju skoraj izginile in da so zato trajne deformacije in s tem trajne strukturne spremembe nepričakovano majhne. To je seveda v protislovju tako s Hoffmeyerjevo hipotezo drsnih ravnin kakor tudi s hipotezo molekularne kinetike, ki sloni na viskoznih, tj. trajnih deformacijah.

Tako smo razkrili nekaj bistvenih povzročiteljev mehano-sorptivnega pojava in poskušali razložiti njegovo delovanje. Odločilni vpliv v MSE imata torej vlažnostni gradient oziroma sorptivne napetosti in sama sestava celičnih sten.

We have found some possible explanations for the causes of MS behaviour.

- The mechano-sorptive effect in adult wood is confirmed.

- The main reason for MS behaviour is the simultaneous action of permanent load stresses and transient three dimensional sorptive stresses, especially in elements of small dimensions.

- The consequence of specific stress distribution in specifically oriented wood tissue is a greater MC - induced dilatation in longitudinal direction in the compressed region. This could be the main reason for the "lifting phenomena" of adult and juvenile wood in the wetting periods.

- By comparison of the MS behaviour of adult and compression wood, the hypothesis that the cell wall structure could be the prevalent factor in MSE is established. Compression wood exhibits viscoelastic creep deformation without typical MSE. Due to its specific cell wall structure such behaviour was expected.

- Although the accumulated deformations during MSE are remarkably high, they practically disappear during MC cycling after unloading and the permanent deformations are very small. This fact, therefore contradicts Hoffmeyer's hypothesis on slip planes as a hypothesis for deformation kinetics, which supposes viscous permanent deformation.

We consider that we have found the most relevant factors and some explanations for the MS behaviour. So, the decisive factor in MSE is the gradient of MC with sorptive stresses, while the cell wall structure also performs an important role.

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