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A thermomechanical explanation for the topology of crack patterns observed on the surface of charred wood and particle fibreboard

Djebar Baroudi[a], Andrea Ferrantelli[a,b], Kai Yuan Li[a,*], Simo Hostikka[a]

[a] Department of Civil Engineering, Aalto University, P.O.Box 12100, Aalto 00076, Finland
[b] Faculty of Civil Engineering, Tallinn University of Technology, 19086 Tallinn, Estonia

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ABSTRACT

In the assessment of wood charring, it was believed for a long time that physicochemical processes were responsible for the creation of cracking patterns on the charring wood surface. This implied no possibility to rigorously explain the crack topology. In this paper we show instead that below the pyrolysis temperatures, a primary global macro-crack pattern is already completely established by means of a thermomechanical instability phenomenon. First we report experimental observations of the crack patterns on orthotropic (wood) and isotropic (Medium Density Fibreboard) materials in inert atmosphere. Then we solve the 3D thermomechanical buckling problem numerically by using the Finite Element Method, and show that the different crack topologies can be explained qualitatively by the simultaneous thermal expansion and softening, taking into account the directional dependence of the elastic properties. Finally, we formulate a 2D model for a soft layer bonded to an elastic substrate, and find an equation predicting the inter-crack distance in the main crack-pattern for the orthotropic case. We also derive a formula for the critical thermal stress above which the plane surface will wrinkle and buckle. The results can be used for finding new ways to prevent or delay the crack formation, leading to improved fire safety of wood-based products.

1. Introduction

Burning wood and other cellulosic materials leave behind a char layer that usually shows a distinct pattern of cracks. During combustion, the char acts as a heat barrier between the combustion zone and virgin material, reducing the burning rate of the uncharred material [1]. The shrinkage and cracking of the char layer have been found to influence the pyrolysis [2,3] and the fire resistance of structures made of cellulosic materials. For instance, the char layer reduces the heat transfer to the virgin material while the cracks enhance it due to the flame attachment to the crack locations [4]. Roberts [5] reported that the charring process of wood took place at approximately 370°C, and that the charred residues greatly influence the combustion processes because they form barriers between flames and unburnt material. However, the charred surfaces exhibit patterns of cracks that will weaken this barrier function. Both mechanisms of crack formation and its effects on combustion process are still unknown. According to Babrauskas [6], still a few decades ago the arson investigators used to attribute the type and spacing of the cracks to the heating rate and possible use of liquid accelerants, but the belief was disproved by Ettling [7] who showed, using furnace experiments, that the exposure temperature alone could explain the observed pattern.

Attempts have been made to model (or explain) the crack-patterns by drying processes, i.e., where the material shrinkage is the driving force [8]; however such theories cannot explain the characteristic crack patterns observed on charred surfaces of wood and fibreboard (Fig. A.1). In the studies of wood pyrolysis, i.e., the thermal decomposition of solid into flammable liquids and gases and solid char, attention has mainly focused on physicochemical processes taking place during and beyond pyrolysis, ignoring the thermomechanical processes occurring below the pyrolysis temperature $T_p \approx 300$°C [3,4,9–11]. Understanding the mechanisms of char cracking can thus lead to improved accuracy of the combustion modeling of wooden materials, enabling more profound considerations of charring behaviors in fire safety and energy technologies.

Our observations of cracking phenomena (Section 2) show that (i) the entire main crack-pattern forms suddenly at all locations and at the same time on the surface, (ii) this occurs *before* any actual charring and (iii) the patterns are quasi-periodic. These are

* Corresponding author at: Department of Civil Engineering, Aalto University, P.O. Box 12100, Aalto 00076, Finland.
E-mail addresses: andrea.ferrantelli@ttu.ee (A. Ferrantelli), kaiyuan.li@aalto.fi (K.Y. Li).

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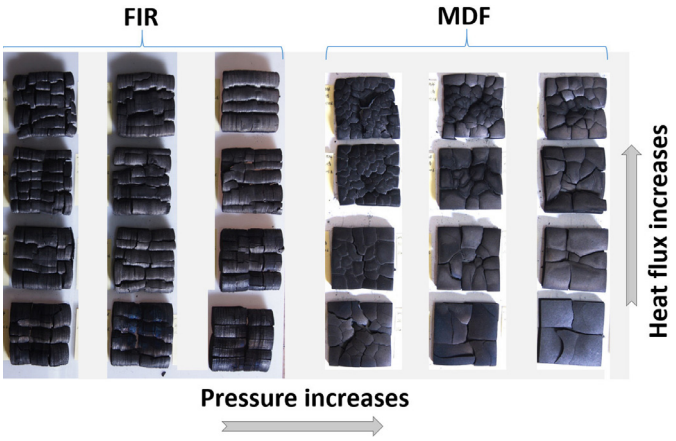

Fig. A.1. Crack patterns at the end of the experiment. Left: plain wood (orthotropy), right: fibreboard (isotropy).

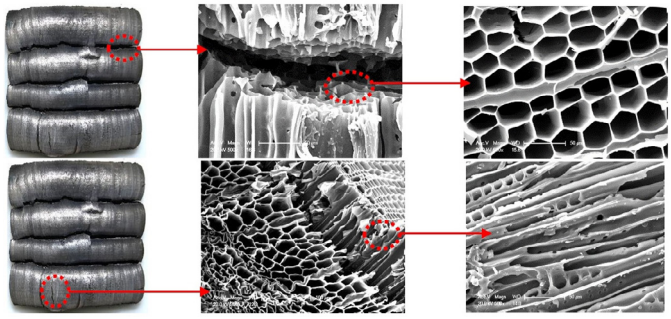

Fig. A.2. Main crack patterns perpendicular to the fibers [21].

typical features of a mechanical instability phenomenon of buckling [12–16].

At temperatures close to but below the onset of pyrolysis at T_p, wood is indeed a natural thermoplastic material [17,18]. The glass transition temperature of dry wood has been observed to be around $T_g \approx 200°C$, at which it simultaneously softens and elongates extensively. Restrain thermal stresses are then induced in the hot layer, and under certain conditions that we explain in Section 5, this eventually leads to wrinkling [17–20].

In this work, we want to find out if the cracking patterns on charred surfaces can be induced by a thermomechanical buckling of a hot thin soft surface layer bonded to a cold, harder elastic substrate (elastic foundation). To investigate the problem, we formulate a model for the experimental conditions where char cracking was observed, and solve it both analytically and numerically to compare the resulting buckling modes with the experimental observations of crack patterns. We do not investigate the crack initiation and propagation processes themselves but focus on the underlying instability phenomenon, to explain the instantaneous and periodic crack patterns. Damage and fracture mechanics studies may be needed in the future, when the effectiveness of the possible means to reduce or delay the crack formation will be evaluated.

As we will show, our thermomechanical model not only reproduces the primary patterns for fir and fibreboard in Fig. A.1. It also explains why the cracks observed for fir (Fig. A.2) are mainly perpendicular to the fibers, where the mechanical resistance properties are stronger, and not parallel, as one would expect by considering only wood shrinkage.

The present paper is organized as follows: in Section 2 we discuss the experimental setup and measurements, while in Sections 3 and 4 we construct a non-linear 3D model that we solve numerically. In Section 5 we perform a dimensional reduction from 3D to 2D to formulate a model for the buckling of a thin layer bonded to an elastic substrate, and derive analytical formulas to identify the controlling parameters of the buckling process. Section 6 is dedicated to our conclusions and Appendix A contains the details of the analytical 2D model, both for the torsion-free and the coupled case.

2. Experimental analysis

2.1. Experimental setup

Pyrolysis experiments were carried out to measure the surface cracking and charring behaviors of planar samples of construction materials, by exposing them to external heat fluxes simulating fire conditions. Nitrogen atmosphere was used to prevent surface oxidation reactions that would transform the charred surface into ash. The experimental rig (Fig. A.3) consisted of three major components: the gas supply system, a low pressure compartment and the control system. The gas supply system provided nitrogen stored in a bottle and air from ambient environment through two pipes. A valve on each pipe controlled the gas flow rate.

The low pressure compartment was 1m long, 1m high and 0.6m wide. Inside the compartment, a 0.3m x 0.3m panel radiator was used to generate uniform radiative heat fluxes towards the samples. The panel radiator was an infrared panel heater that could generate an incident heat flux up to 100 kW/m^2, with the highest temperature being 1800°C. More details are available in [21].

The panel radiator was hanged at two tracks to adjust its position. The vertical distance between the panel and sample surfaces was 30mm. The sample holder was made of Kaowool, and an electric balance was used to weight the sample while two thermocouples measured the temperatures both inside the sample and on its surface. A digital camera was placed in front of the observation window to record the charring process. The control system included a stabilization tank, a vacuum pump and a central control unit with a touch screen to manage the experimental process.

The charred samples were sent for SEM experiments to examine the microstructures of char and char fissures after pyrolysis. The SEM equipment is XL30 ESEM-TMP made by Royal Philips of the Netherlands, it can be used for micro-morphology research of electrically conductive solid materials.

2.2. Materials

The current study uses Medium Density Fibreboard (MDF), made by a local manufacturer, and natural fir. The MDF samples are 100mm long, 100mm wide, 15mm thick with a bulk density $\rho_{MDF} = 730 \pm 17$ kg/m^3. The fir samples are 100mm long, 100mm wide, 25mm thick with a bulk density $\rho_{fir} = 363 \pm 18$ kg/m^3. According to the manufacturer, the MDF panels are made from pine tree, with approximately 10% of resin and wax as the additives. To evaluate the grain effect of natural wood, the fir samples were cut parallel to the grains and symmetrically with respect to the center of the annual rings.

The samples were dehydrated in an oven at 95–100°C for at least 24 h to remove the moisture. Their mass was monitored every 2 h during the drying process to ensure mass stabilization. The samples were then sealed in plastic bags and weighted again after cooling, to ensure that any change in the moisture content was insignificant. After the pyrolysis experiments, the charred samples were split to small particles with or without fissures for SEM experiments. As the charred samples were not electrically conductive, they were treated by splashing conductive material at the surfaces before the SEM experiments.