Construction and Building Materials 88 (2015) 126–133

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

An empirical prediction law for quasi-static nail–plywood penetration resistance

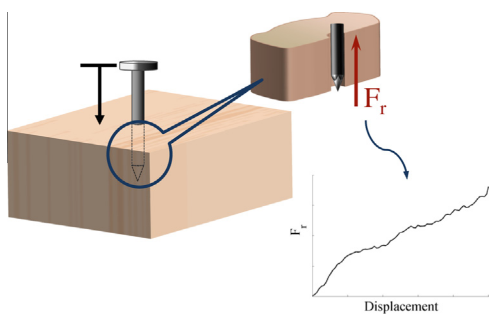
Z. Nili Ahmadabadi, Frédéric Laville, Raynald Guilbault *

Université du Québec, École de technologie supérieure, Department of Mechanical Engineering, 1100 Notre-Dame Street West, Montreal, Quebec H3C 1K3, Canada

HIGHLIGHTS

- Study of tribo-dynamic interactions at wood–nail interface during fastening.
- Analysis of various nail geometries and sizes, and plywood types.
- Dimensionless parameters studied over quasi-static velocity range.
- Penetration resistance force (*PRF*) composed of deformation–fracture and friction forces.
- Development of a *PRF* prediction model for plywood–nail combinations.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form 29 January 2015
Accepted 12 April 2015
Available online 24 April 2015

Keywords:
Nail
Penetration resistance
Wood-product
Plywood
Deformation–fracture force
Friction force
Emperical prediction-model

ABSTRACT

This paper presents an empirical model predicting penetration resistance forces (*PRF*) imposed on nails when penetrating plywood samples at quasi-static velocities (20–500 mm/min range). The formulation covers various nail geometries and sizes and three plywood types. A universal testing machine was used to drive the nail into the wood samples at constant speeds. The machine measured *PRF* as a function of the position. The analysis reduces the studied factors to dimensionless parameters. More than 200 experiments were conducted over the parameter space, and the final formulation derives from regressions. Test cases showed an overall precision of *PRF* prediction above 89%.

1. Introduction

The present paper describes and formulates the tribo-dynamic interactions developing between wood-based products and metal nails during fastening process motions.

For centuries, nails have been used to connect wood pieces. Until the emergence of nail guns, which revolutionized the speed of construction in the 50s, hammering was the only nail fastening option. Even though emitted noise may cause health problems, nail guns have been used despite generating high noise levels.

Over the years, the different nail geometries have been modified to make the fastening process more efficient by increasing the withdrawal resistance force and the load resistance of the connections [1–4]. Nevertheless, nail improvements have never been considered from a noise or vibration reduction perspective.

Under normal operation conditions, nail guns generate noises and vibrations. Improving the concept design to reduce the emission levels certainly represents an ineluctable operation. However, modifying the tool design requires a precise

* Corresponding author.

http://dx.doi.org/10.1016/j.conbuildmat.2015.04.011
0950-0618/

Table 1
Parameter sets 1 and 2.

	Parameters	Dimension
Parameter set 1	(1) Wood density (ρ)	ML^{-3}
	(2) Wood hardness (H_M)	MT^{-2}
	(3) Nail shank type (ST)	–
	(4) Nail diameter (D)	L
	(5) Nail length (NL)	L
Parameter set 2	(6) Penetration velocity (v)	LT^{-1}
	(7) Displacement (y)	L

understanding of its dynamics, as well as the influence of any modification. A dynamic model of the system is therefore essential.

Zhong and his colleagues presented a simplified mathematical pneumatic nail gun model [5]. The authors simulated the air chamber pressure and considered the piston as acting against a constant penetration resistance force. Later, Fujie [6] examined the gas dynamics influence on the performance of a pneumatic nail gun. This investigation also reduced the nail penetration resistance to a constant force. However, it may be assumed that neglecting the complex tribo-dynamic conditions involved in the nail penetration process affects the model precision.

Despite numerous studies on the resistance of wood-based connections [7–24], only two papers [23,24] have examined nail penetration tribo-dynamic aspects. In Ref. [23], Villaggio studied nail penetration into soft materials as a result of hammering. The author idealized the nail as a cylindrical shaft, and developed an analytical formulation of the penetration rate per hammer blow. For their part, Bartelt and his coauthors [24] employed numerical models to simulate impact penetration of nails driven by power-actuated fastening tools into hard construction materials such as steel or concrete.

Since wood products correspond to highly heterogeneous domains, the precise numerical modeling of such materials results in computationally onerous simulations. Therefore, to ensure precise and rapid representations, the present study derives a nail penetration model from experimental measurements. The objective is to prepare a formulation predicting the nail penetration resistance force as a function of nail size and type. Since this paper is seen as the first part of a broader investigation, the wood products examined are restricted to plywood, and the penetration speed range to quasi-static conditions. To eliminate the possible influence of acceleration, the penetration speed is maintained

Table 2
Hardness modulus, density values, and moisture content.

	DFP	*CSP*	*PP*
H_M (N/mm)	560.11	371.77	478.96
ρ (kg/m^3)	543.59	449.71	464.00
Moisture content (%)	5.7	5.6	5.6

Table 3
Nail shank types.

Nail penny size	Smooth nails	Annularly threaded nails	Helically threaded nails
3d	✓	✓	
4d	✓	✓	
6d	✓		
8d	✓	✓	✓
10d	✓	✓	✓
12d	✓		
16d		✓	✓

constant. The measurements are all realized on a universal testing machine. In order to extend the prediction formula application range, the analysis first reduces the studied factors to dimensionless parameters. Section 2 describes the experimental procedure. Section 3 analyses the penetration resistance force (*PRF*) results, and presents a parametric study. Finally, the empirical nail penetration model is derived from regression analyses in Section 4.

2. Experimental procedure

2.1. Influential parameters and dimensional analysis

Initial qualitative evaluation indicated that the parameters controlling *PRF* may be collected in two classes mainly: (1) the size and material properties (parameter set 1), and (2) the penetration process (parameter set 2).

Parameter set 1 includes: (1) the wood density, (2) the wood hardness modulus, (3) the nail geometry type or the nail shank type, (4) the nail diameter, and (5) the nail length. It may be intuitively supposed that parameters 1 and 2 have direct and proportional effects on *PRF*; denser or harder materials should result in *PRF* of greater amplitude. While the same information could be deduced from the wood-specific gravity combined with moisture content, the wood density parameter allows a reduction of the number of parameters included in the analysis. The hardness modulus parameter describes the material resistance to penetration deformation. moreover, since the steel Young modulus is significantly higher than the plywood Young modulus, the analysis assumes that the nails are perfectly rigid.

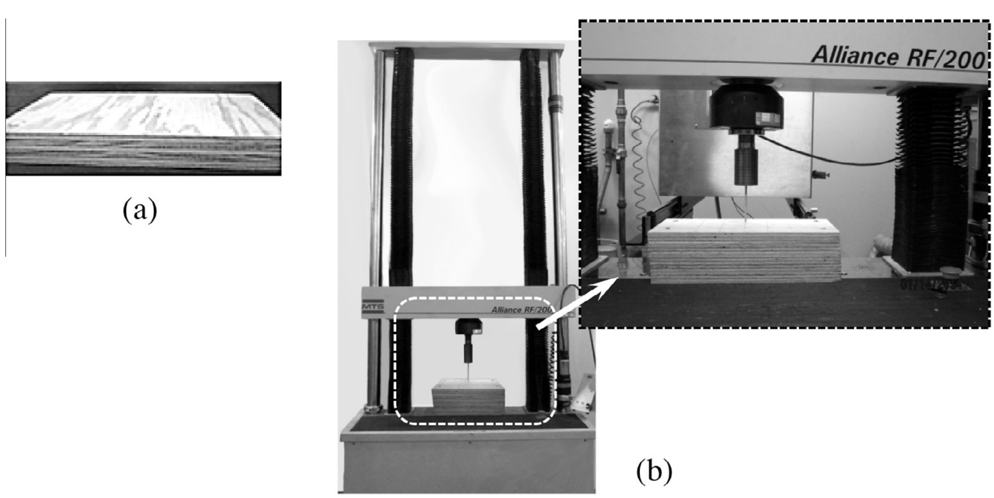


Fig. 1. (a) Douglas-Fir plywood panel, and (b) experimental set-up.