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# Modeling of asphalt roof shingle-sealant structures for prediction of local delamination under high wind loads

Brendan P. Croom [a], Michael A. Sutton [b,*], Xing Zhao [b], Fabio Matta [c], Rahim Ghorbani [c]

[a] Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, USA
[b] Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA
[c] Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC, USA

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ABSTRACT

An analytical model based on beam-on-elastic foundation (BOEF) principles is formulated and employed to simulate the structural response of a realistic asphalt shingle-sealant system under high wind loads. The system consists of individual three-tab shingles that are discretely bonded to the underlying shingles and subjected to differential out-of-plane pressures that are associated with high wind loads. Relevant mechanical properties for a typical modern asphalt shingle and sealant were determined experimentally and input in the proposed structural model. The model was then used to estimate the applied energy release rate, $G$, for the sealant strip as a function of length, location, and applied uplift pressures on the shingle. Results indicate that the $G$ values are highly sensitive to sealant strip location and sealant length, where sealant length is defined to be along the perpendicular direction between the nail line and leading edge of the shingle, and that the sealant strip location in typical modern shingles is roughly optimized to ensure a balanced value of $G$ at the inner and outer sealant strip edges. However, predictions also indicate that $G$ could be further reduced by using longer sealant strips that are slightly shifted towards the leading edge of the shingle, thereby decreasing the potential for failure. Additional BOEF model simulations were performed using full-field shingle uplift displacements as input to determine the potential for estimating the average uplift pressures imparted on asphalt shingles under high wind loading conditions. Promising results were obtained regarding the suitability of the proposed BOEF-based inverse analysis technique to estimate shingle uplift pressures. In addition, $G$ values that are scaled for high pressures associated with extreme wind conditions, and resulting in sealant separation, are in qualitative agreement with an estimate of critical energy release rate, $G_c$, based on the results of standard direct tensile tests reported in the literature.



## 1. Introduction

Modern asphalt-based composite roof shingles are subjected to a variety of environmental and loading conditions that affect their performance [1]. The focus of the study presented in this paper is the effect of high winds on the deformation and failure of asphalt shingles. Shingle uplift under wind loads is a function of the negative pressure caused by flow separation at the leading edge of a shingle, and positive (stagnation) pressure below the shingle, as illustrated in Fig. 1. This peculiar mechanism was first described and translated into a quantitative model by Peterka et al. [2,3]. This model led to the definition and implementation of the current ASTM D7158 [4] and ASTM D3161 [5] test standards. However, it is well documented that even recently installed asphalt shingles that were rated for resistance against 150-mph (*i.e.*, H-rating per ASTM D7158 [4]) and 110-mph 3-s gusts (*i.e.*, F-rating per ASTM D3161 [5]) suffered extensive damage when exposed to winds with 115 mph or less 3-s gusts in Hurricane Ike [6–8].

This underperformance is due in part to the fact that the current standard test methods [4,5] are representative of idealized shingle conditions and may not adequately simulate the effects of real-world high wind loads. In fact, the fundamental understanding of uplift forces as a function of wind velocity, and the associated failure mechanisms, is hindered by the difficulty to accurately quantify and map with good spatial resolution the uplift deformations and pressures imparted on shingles during wind load tests. For example, attaching conventional point-wise sensors (e.g., strain gauges, load cells, pressure taps) will affect the mass and stiffness

* Corresponding author at: 300 Main Street, Room A129, 29208 Columbia, SC, USA. Tel.: +1 (803) 777 7158; fax: +1 (803) 777 0106.

*E-mail addresses:* bpc2nr@virginia.edu (B.P. Croom), sutton@sc.edu (M.A. Sutton), zhao29@email.sc.edu (X. Zhao), fmatta@sc.edu (F. Matta), ghorbanr@email.sc.edu (R. Ghorbani).

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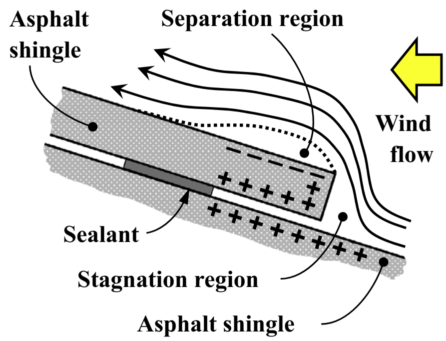


**Fig. 1.** Schematic of up-roof wind flow and resulting differential pressure on shingle (after Peterka et al. [2,3]).

of shingle specimens. Recent research [9] demonstrated the feasibility of performing accurate non-contacting and essentially full-field displacement measurements on asphalt shingles subjected to high wind loads using three-dimensional digital image correlation (3D-DIC) [10,11]. In perspective, inverse analysis methods may be enlisted with full-field displacement measurements to estimate mechanical parameters of interest (e.g., [12–16]) and out-of-plane pressure profiles (e.g., [17,18]) under realistic loads conditions. To this end, the availability of a mechanics-based shingle uplift model that is capable of simulating shingle as well as sealant behavior becomes critical.

As a result of shingle uplift under wind loads, system failure may occur due to sealant adhesive or cohesive failure (i.e., at sealant-shingle interfaces or within the sealant) [19–21], or within the shingles themselves. A physics-based measure of strength is the energy per unit area required for separation, i.e., energy release rate, which is designated herein as $G$. While $G$ (as well as its critical value associated with delamination, $G_c$) can be estimated from physical experiments (e.g., ASTM D6381 [22]), a mechanics-based shingle uplift model can be instrumental for a correct interpretation of results, as $G$ is highly sensitive to the type of loading (e.g., peeling or direct tension) and loading rate [19].

The need for a mechanical model is further highlighted by recent studies on environmental aging effects on shingle uplift resistance. It has been shown that natural aging and exposure to moisture, ultraviolet radiation and thermal fluctuations result in progressive degradation of the uplift resistance of asphalt roof shingles [23–27]. However, standardized artificial aging methods (e.g., [28–30]) inevitably pose limitations in reproducing peak uplift forces and failure modes as experienced in naturally-aged shingles (e.g., [31]). Acknowledging the difficulty in replicating natural shingle aging and realistic loading conditions, this paper introduces an energy release rate model for use as a theoretical backdrop towards improving current test standards, and comparing the uplift resistance of newly-installed, as well as naturally- and artificially-aged shingles, based on the critical energy release rate, $G_c$, associated with delamination.

The proposed analytical model is based on beam-on-elastic foundation (BOEF) principles and aims to represent the response of an asphalt shingle that is nailed at one end, locally bonded to a substrate near the leading edge and subjected to differential pressure loading under high winds. First, the model is formulated and defined for a representative shingle system using experimentally-determined mechanical properties from shingle and sealant coupons. The model is then used to: (a) identify trends in the applied energy release rate for the sealant as a function of sealant length, sealant location, and applied out-of-plane pressure on the shingle; and (b) discuss the potential for using the model with measured shingle displacements (e.g., based on 3D-DIC full-field displacement maps) to estimate the pressure imparted on the shingle under high wind loads. As part of the modeling effort, an analysis is performed to identify key groups of non-dimensional parameters that contain energy release rate and describe the relationship between relevant geometric, material and loading parameters.

## 2. Analytical model of shingle-sealant structure

Fig. 2 shows a schematic of a modern three-tab composite asphalt shingle system, along with a blow-up of the internal construction. Each shingle has a sealant strip (either continuous or intermittent) that is typically ~13 mm wide, extends across the width of the shingle and adheres to the staggered shingles beneath. All shingles are nailed along one side directly into the roof panel that typically consists of a plywood sheet reinforced from below by timber ribs and joists.

Fig. 3 shows a schematic of the BOEF model that was used to represent the shingle-sealant structure. Conceptually, the BOEF model is intended to represent the response of a typical region such as shown in Fig. 2. This assumption is consistent with assuming that the entire tab of the shingle deforms in the same manner along its entire width, providing a relatively simple analytical model to describe the response of a "unit width" in the $z$-direction (perpendicular to $x$ and $y$ in Fig. 3) section. Table 1 provides a list of all BOEF model parameters. As shown in Fig. 3b, the shingle of length $l = l_1 + l_2 + l_3$ is modeled as a beam with flexural stiffness $EI$. The sealant strip of length $l_2$ is modeled as an elastic foundation with stiffness $S$ (units $FL^{-3}$). The applied pressures $p_1$ and $p_3$ (units $FL^{-2}$) are assumed to be independent loading parameters over the lengths $l_1$ and $l_3$, respectively, on the shingle.[1] Since $l_1$ and $l_2$ are variables, both the location and length of the sealant along the shingle (axis $x$) can be varied to quantify their effects.

### 2.1. Mathematical formulation

Based on Euler–Bernoulli beam theory and using the parameters defined in Table 1, the shingle out-of-plane (i.e., $y$-direction in Fig. 3) deflection is determined through Eq. (1), from which analytical solutions for $w_i(x)$ ($i = 1$, 2 and 3 associated with shingle Region 1, 2 and 3, respectively, in Fig. 3b) can be expressed per Eqs. 2–4. It is noted that Eqs. 2–4 are linear with respect to the 12 unknown constants of integration in addition to $p_1$ and $p_3$, which facilitates the solution of the inverse problem as described in Section 2.2.

$$EI\frac{\partial^4 w_i}{\partial x^4} = F_i(x), F_i(x) = \begin{cases} p_1(x) & \text{for } i = 1 \\ -Sw_i(x) & \text{for } i = 2 \\ p_3(x) & \text{for } i = 3 \end{cases} \quad (1)$$

$$w_1(x) = \frac{1}{EI}\left(C_1 + C_2 x + \frac{C_3 x^2}{2} + \frac{C_4 x^3}{6} + \frac{p_1 x^4}{24}\right) \quad (2)$$

$$w_2(x) = C_5 e^{\alpha x}\cos(\alpha x) + C_6 e^{\alpha x}\sin(\alpha x) + C_7 e^{-\alpha x}\cos(\alpha x) + C_8 e^{-\alpha x}\sin(\alpha x)$$
$$\alpha = \left(\frac{S}{EI}\right)^{0.25} \quad (3)$$

$$w_3(x) = \frac{1}{EI}\left(C_9 + C_{10} x + \frac{C_{11} x^2}{2} + \frac{C_{12} x^3}{6} + \frac{p_3 x^4}{24}\right) \quad (4)$$

[1] While line loads (units $FL^{-1}$) are typically used in beam problems, pressure loads (units $FL^{-2}$) are used in this paper for consistency with uplift pressure values. A beam with unit width, $W$ = 1 m, is assumed, which makes these two load types functionally equivalent due to the relation *line load* = *pressure*×*width*.