A Model for the Characterization of the Scrap Tire Bale Interface

B. J. Freilich[1] and J. G. Zornberg[2]

[1]Graduate Research Assistant, Department of Civil, Environmental, and Architectural Engineering, The University of Texas at Austin, email: bjfreilich@hotmail.com
[2]Professor, Department of Civil, Environmental, and Architectural Engineering, The University of Texas at Austin, PH: (512) 472-3595, email: zornberg@mail.utexas.edu

ABSTRACT

Tire bales are large rectangular blocks consisting of compressed whole scrap tires that are an alternative lightweight fill material to the tire shred used in highway structures. The bales are typically assumed to act as discrete blocks for short term conditions, in which the controlling mode of failure is sliding along the jagged surfaces of the bales. Stresses along the irregular tire bale surfaces were defined using a planar footprint area of the bale, defined as the product of the average bale length and width. An alternative model for the characterization of the three-dimensional tire bale surface was developed that represented the actual behavior along the bale surface during shear deformations. The model, which was based on force equilibrium, was used to calculate the geometric parameters of tire bale interface controlling the interface shear resistance using data obtained from large scale direct shear testing of the tire bales and small scale testing of flat tire plates.

INTRODUCTION

Scrap tire bales, which consist of whole tires compressed into a block, are an alternative to the tire shred fills used in highway structures. The benefit to utilizing the whole tires within the bales is that there is no processing (shredding) required, and the bales are easily placed into the structure without mixing or compaction. The design of tire bale structures has been accomplished by assuming the bale geometry is a perfect rectangular block, referred to as the footprint interface model assumption. The footprint model is a method used to simplify the calculation of interface stresses between layers of tire bales. Interface stresses are distributed uniformly along the assumed continuous interface failure area defined using the average bale dimensions (Zornberg et al. 2004, LaRocque 2005, and Winter et al 2006). Although the assumption leads to a simple design and analysis of the tire bale structure, the behavior and geometric parameters of the irregular tire bale surface that control the interface strength are ignored. A model was therefore developed in which the actual physical characteristics of the tire bale interface were quantified. Modeling the physical characteristics was a useful tool in determining how different design considerations, such as the presence of moisture, soil infill and the tire bale stacking arrangements, influenced the interface strength.

The surface of the tire bale is characterized by a series of jagged, uneven and variable tire surfaces, or tire ridges, protruding out of the bale mass. The strength of

the tire bale interface, or the contact surface between two layers of bales, is controlled by the deformations along the discrete contact points between the tire ridges. The objective of the analysis presented in this paper was to determine the geometric characteristics of the three-dimensional tire ridge contacts that control the strength of the tire bale structure. Due to the variable and irregular surfaces of the tire bales, a simplified model was developed in which the tire ridges along the interface were represented with a series of symmetric and homogenous ridges. The geometric parameters of the simplified model were determined using results from a series of large scale testing of tire bales and small scale testing of flat tire plates.

THE TIRE BALE INTERFACE STRENGTH DEFINED USING THE FOOTPRINT INTERFACE MODEL

The standard tire bale is a block of 70 to 100 compressed whole scrap tires bound by a series of steel wires (Figure 1). The bales are assumed to behave as rigid blocks for short term conditions, in which the baling wires remain intact and sliding along the tire bale surfaces is the controlling mode of failure. The strength of the tire bale interface is therefore required for the design and stability analysis of the tire bale structure.


Figure 1. Photograph of the Standard Tire Bale.

The interface strength was determined utilizing a large scale direct shear testing procedure (Figure 2). The direct shear test was used to determine the horizontal shear load required to displace (slide) a tire bale along a layer of stationary tire bales.


Figure 2. The Large Scale Direct Shear Test Setup for Tire Bales.

Interface stresses were calculated using the footprint interface model, in which the interface geometry was assumed to be a continuous and flat contact surface. Stresses were distributed uniformly over the continuous footprint interface of the tire bale structure, which was an incorrect assumption due to the jagged and irregular bale surfaces. The peak interface shear stresses versus the applied normal stresses for a series of dry tire bale interface tests are presented in Figure 3. The failure points were represented with a Mohr-Coulomb failure envelope characterized by a cohesion of 21 psf and a friction angle of 35°. The cohesion intercept was an indication that the actual interface was not a flat surface as assumed when using the footprint interface model.

The chart shows data with the equation:
$$y = 0.7113x + 21.372$$
$$R^2 = 0.971$$
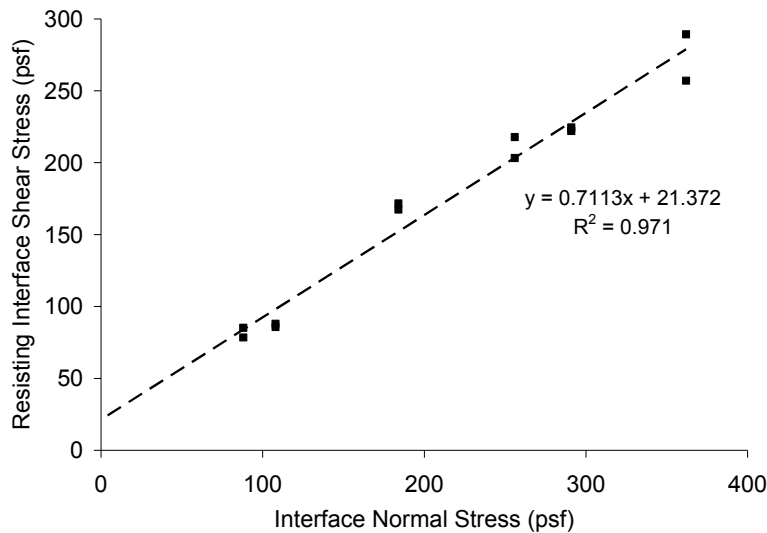
Figure 3. The Peak Interface Shear Stress and Resulting Failure Envelope from Direct Shear Testing of Tire Bales.

Small scale tests were conducted on flat tire plates to determine the shear strength parameters along an actual flat tire interface with constant contact area. The plates were tested in a modified soil direct shear testing apparatus, in which a circular tire plate was sheared across a larger rectangular flat tire plate (Figure 4). The tire plates were cut from a series of scrap tires obtained from random tire stockpiles.
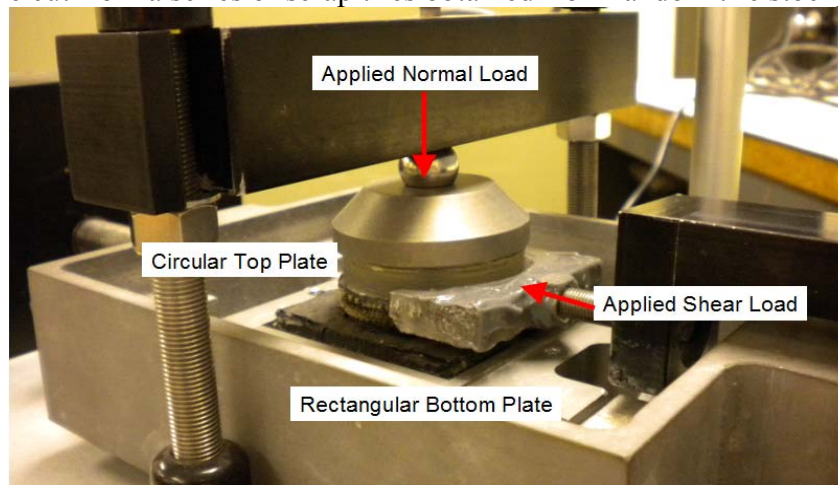
Figure 4. Small Scale Direct Shear Testing of Flat Tire Plates.

Results from the direct shear testing of the tire plates are provided in Figure 5 for two tire plate direct shear tests. Tire plate interface strength results provided by Yang et al. (2002) are also included. The strength of the flat tire interfaces were represented with linear Mohr-Coulomb failure envelopes with cohesions of zero (0) and friction angles ranging from 29° to 39°. The range in friction angles was attributed to the different conditions of the scrap tire plates used for the tests.
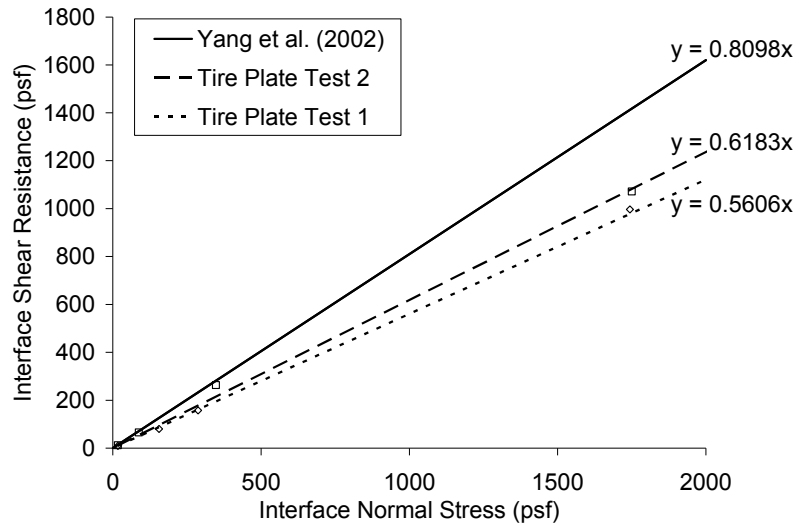
**Figure 5. Interface Shear Strength Versus Normal Load for Flat Tire Plates.**

The results from the large and small scale testing of the scrap tires provided evidence that the strengths along the flat tire and the jagged tire bale interfaces were controlled by different mechanisms. The use of the footprint interface model over-simplified the geometry of the tire bale interface, combining the influence of the geometric parameters controlling the interface strength into the cohesion and friction angle strength parameters. In order to better understand the behavior along the interface which controlled the strength measured during the large scale direct shear test, a more detailed model was developed.

THE SIMPLIFIED TIRE BALE INTERFACE MODEL

The compression of the whole scrap tires within the tire bale mass resulted in a series of tire ridges that protruded out along the surface of the tire bale mass. The characterization of the tire ridges was difficult due to the variable placement, inclination, and height of the ridges. A simplified model of the three-dimensional interface was therefore developed in which the tire ridges were represented with a series of symmetric and homogeneous ridges. The benefit of using the simplified interface was that the characteristics of the model were similar to that of the actual interface, in which the interface shear strength is controlled by the sliding of the tire ridges past each other. The geometric characteristics of the simplified model represent the average conditions of all the tire ridge contacts along the interface.

Illustrations of the footprint interface model and simplified interface model are provided in Figure 6. The simplified interface model reduced the irregular actual tire bale interface to a finite number of tire ridges of equal height, spacing, and

inclination. The footprint interface model was a further simplification of the simplified interface model, in which the inclination of the tire ridges was reduced to zero and the surface of the tire bales was assumed to be perfectly flat, resulting in a continuous contact along the interface.
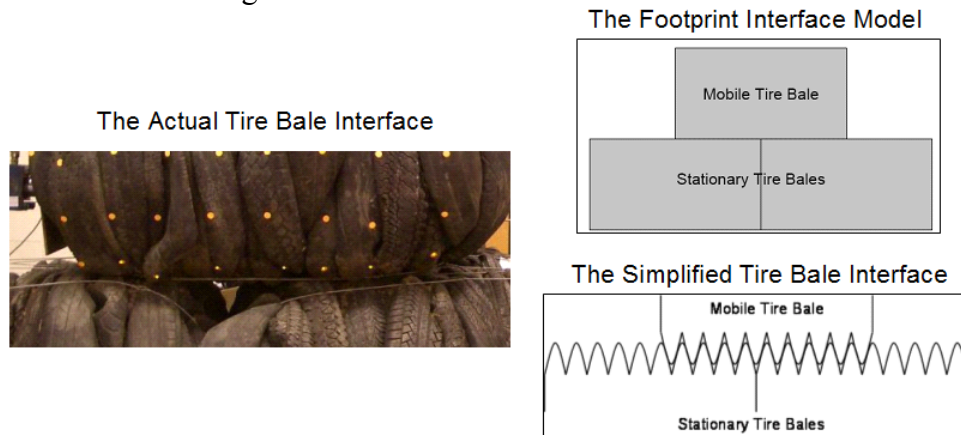
Figure 6. Illustrations of the Footprint Interface Model and the Simplified Interface Model for Tire Bales.

The geometric parameters needed to characterize the contact areas for the simplified interface model were the inclination of the tire ridges (dilatancy angle), the actual contact area between the ridges, and the initial opening along the interface. An illustration of the geometric parameters is provided in Figure 7.
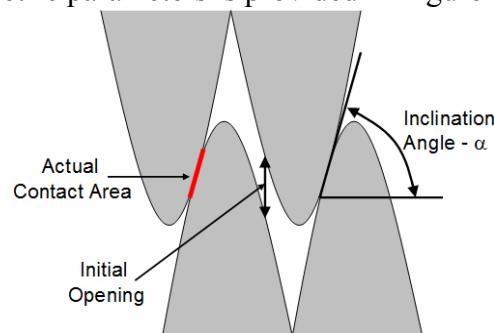

Figure 7. Illustration of the Tire Ridge Geometric Parameters Needed for the Simplified Interface Model.

Each of the geometric parameters needed for the simplified interface model were calculated utilizing laboratory data and force equilibrium equations. The determination of the simplified interface model parameters is outlined in the following sections using the results from a series of large scale direct shear tests for three dry standard tire bales.

The Dilatancy Angle. The dilatancy angle of the simplified interface represents the average inclination of the tire ridge contact surfaces along the tire bale interface. The horizontal shear displacements along these inclined contact areas resulted in the cohesion intercept determined using the footprint interface model. Force equilibrium equations were used to determine the average dilatancy angle of the tire ridges at failure using the shear and normal loads measured during the direct shear testing. Force equilibrium equations were defined for both the footprint interface and the

simplified interface models, as illustrated in Figure 8. The normal (N) and shear (T) loads applied along both interface models were the same.
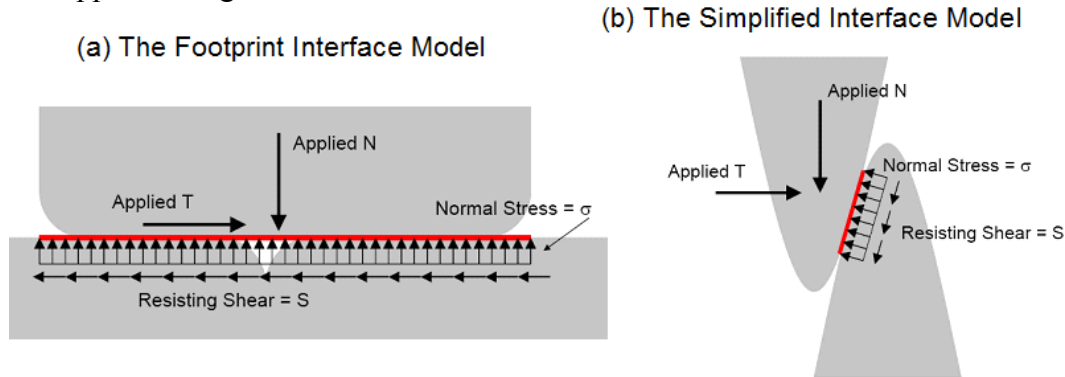

Figure 8. Illustration of the Applied Loads and Resultant Stresses along the Two Tire Bale Interface Models.

Force equilibrium equations in the horizontal and vertical directions were defined for both models. The equilibrium equations were combined and rearranged so that only the applied shear load (T) was on the left hand side of the equation, as follows:

$$\text{Footprint Model}: \quad T = c_{tb} \cdot A_F + N \cdot \tan\phi_{tb}$$

$$\text{Simplefied Interface Model}: \quad T = \frac{N}{1 - \tan\phi_{tp} \cdot \tan\alpha} \cdot \left(\tan\phi_{tp} + \tan\alpha\right)$$

Where N and T are applied normal and shear loads, respectively, A_F is the footprint area, c_{th} and ϕ_{tb} are the tire bale strength parameters utilizing the footprint area, ϕ_{tp} is the frictional strength along the tire ridge contacts, and α is the dilatancy angle. Only the equation developed for the simplified interface model contained a geometric parameter describing the actual tire bale interface. The average dilatancy angle (α) was determined assuming a tire ridge contact strength (ϕ_{tp} = average friction angle from tire plate testing) and using the measured values of T and N at the peak (failure) conditions determined from the large scale direct shear test (Figure 9).
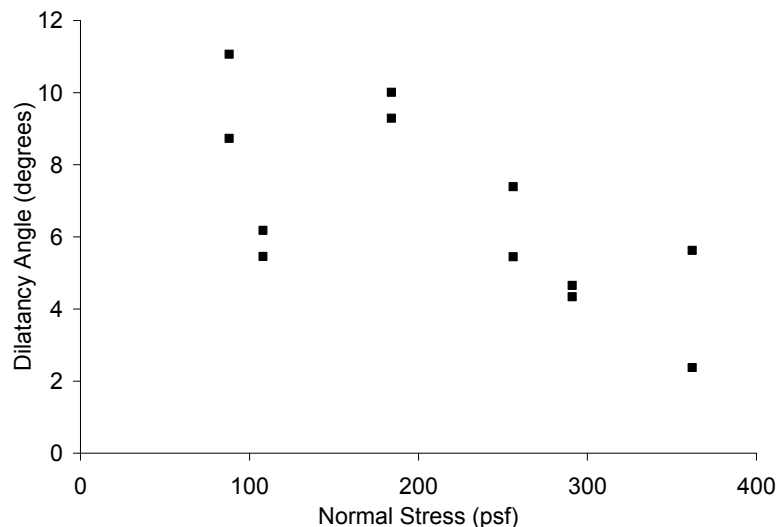

Figure 9. The Average Dilatancy Angle at Failure for the Simplified Interface.

The force equilibrium analysis of the tire ridge contacts provided evidence that the inclination angle along the tire ridge contacts changed with the applied normal and shear loads. The change in contact angle with applied loads should result in a non-linear failure envelope. However, the small change in dilatancy angle over the stress range tested would result in only a small curvature that could not be differentiated from the variability of the tire bale interface strength data.

The Actual Contact Area.   The actual tire ridge contact areas could not be determined using the force equilibrium equations developed in the previous section. A tire bale stamp test was therefore developed to directly measure the actual contact area. The test consisted of placing a thick piece of paper on top of a tire bale layer, painting the bottom surface of a top bale, and then pressing the two layers of bales together, as illustrated in Figure 10. The test was conducted for a range of applied normal loads and for a two and three bale stacking arrangement.
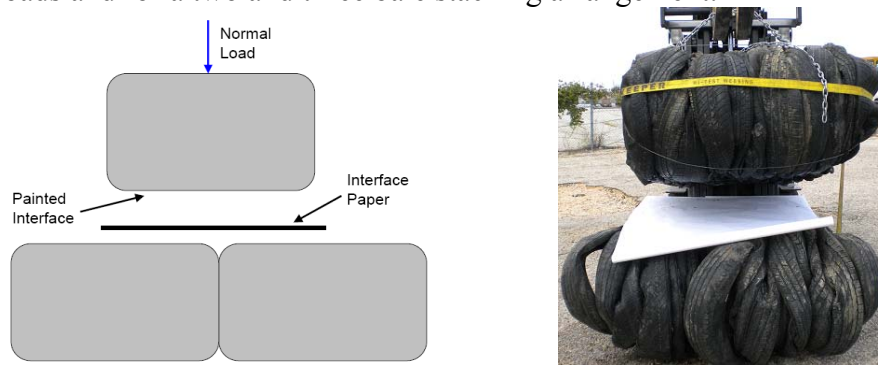

Figure 10. Illustration of the Tire Stamping Method to Measure the Actual Contact Area along the Tire Bale Interface.

The result of the testing program was a series of two dimensional pictures of the discrete three-dimensional contact areas along the interface (Figure 11). Digital photographs of the tire stamps were converted to black and white images to determine the ratio of the black and white pixels. The pixel ratio was used to determine the actual contact area along the interface for the range of normal loads applied during the direct shear test (Figure 12). The only assumption required for the tire stamp testing was that the interface contact area was only dependent on the applied normal load, and not on the applied shear stresses.


Figure 11. Digital Photograph of a Tire Bale Interface Stamp.
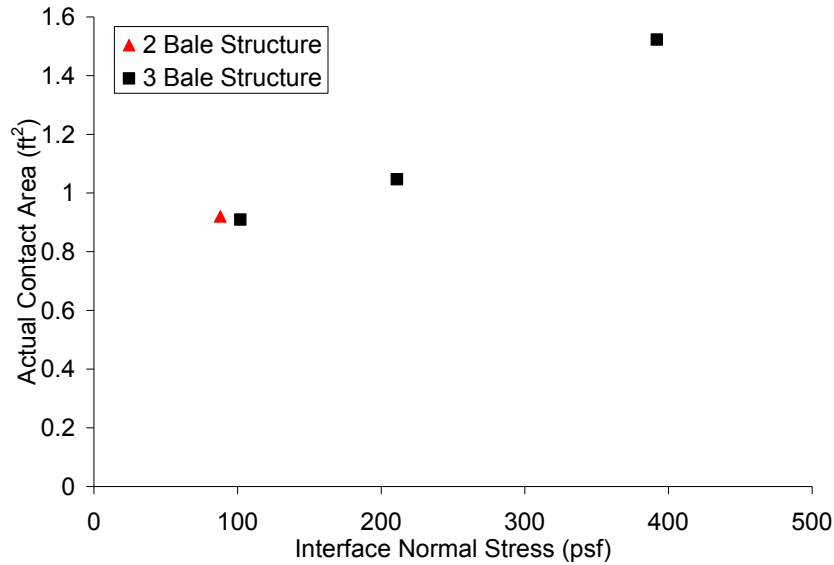
Figure 12. Actual Tire Bale Interface Contact Area with Applied Normal Load.

The actual contact area between the tire ridges was less than the assumed footprint area of the tire bale (a value of 22.5 ft^2 is typically assumed) and increased with applied normal stresses. In addition, utilizing different tire bale stacking arrangements did not influence the contact area along the interface.
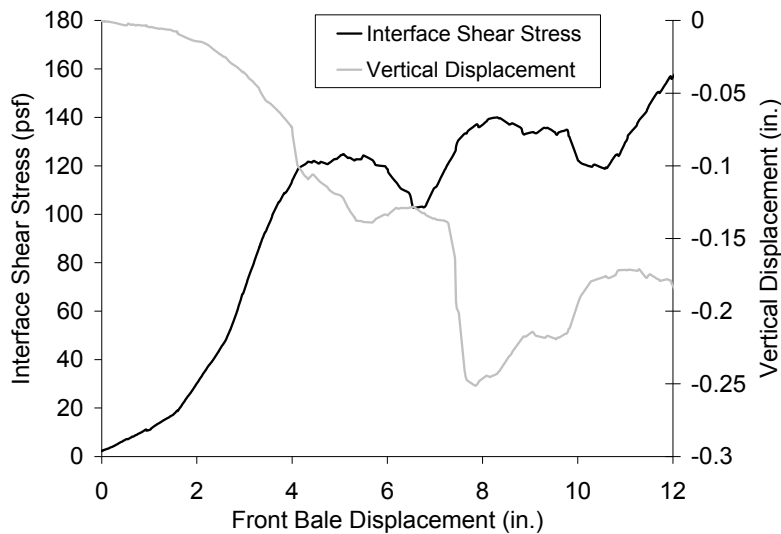
The Initial Opening of the Interface. The initial opening of the tire bale interface was a parameter used to represent the deformation of the tire bale interface required to reach failure. The horizontal displacement of the tire bale was defined as the rigid displacement of the mobile tire bale (deformation measured at the rear of the bale) before reaching failure (Figure 13). The increase in the rigid displacement with applied normal stress was attributed to an increase in the deformation of the tire ridge contacts before reaching peak conditions (failure).
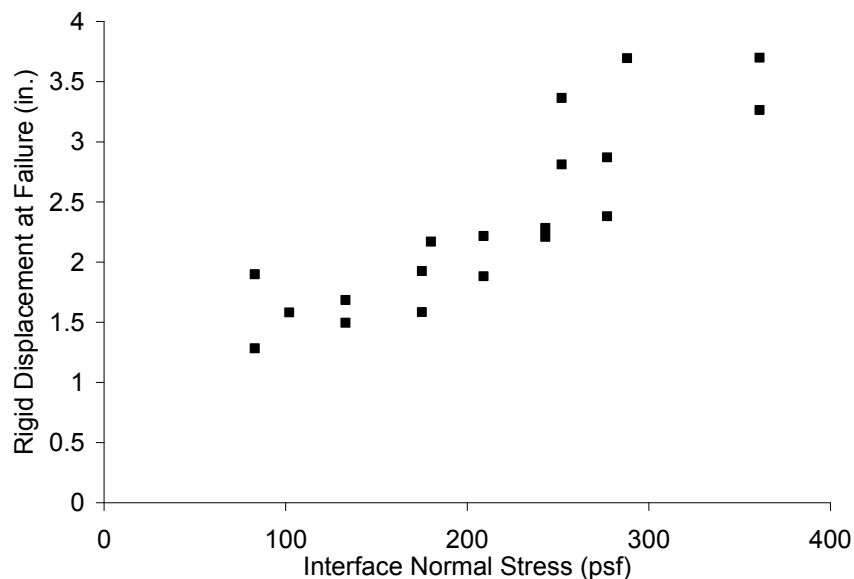
**Figure 13. The Horizontal Rigid Displacement of the Mobile Tire Bale.**

A vertical deformation of the tire bale was also measured during the direct shear testing. The average vertical deformation of the mobile tire bale, measured with a vertical LVDT, and the mobilized shear resistance are plotted against the horizontal bale displacement in Figure 14. The curves provided evidence of a relationship between the interface shear stresses and the vertical displacement of the tire bale. The downward displacement of the tire bale, which corresponded to an increase in interface shear stress, implied the tire ridges were coming into contact and approaching the critical placement. An upward displacement of the tire bale, which corresponded to a decrease in the interface shear stress, implied that the critical placement (peak shear resistance) along the tire ridges was reached resulting in a weaker interface.

Figure 14. The Vertical Displacement and Shear Resistance along the Interface.

The horizontal displacement and downward movement of the mobile tire bale implied that the tire ridges were moving from an initial (weak) position into a critical (or peak) condition along the interface (Figure 15). The critical condition along the tire ridge contacts (when the peak shear strength is mobilized) was characterized by both a rigid displacement of the mobile tire bale along the interface and deformation of the tire ridges. The initial opening of the tire bale interface was therefore a parameter that takes into account both the rigid movement of the tire bale into the critical placement and the deformation of the tire ridges required to reach the peak interface stress.
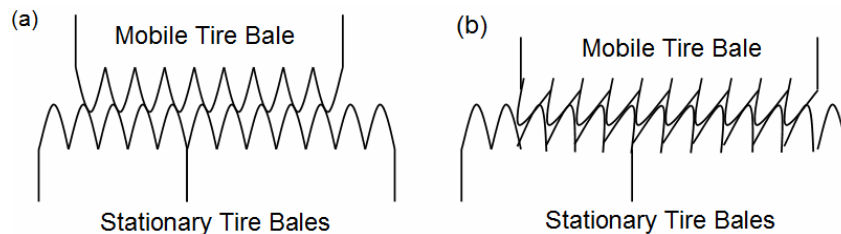
Figure 15: The (a) Initial and (b) Critical Placement of the Tire Ridges.

Due to the variability of the tire bale surface, not all tire ridges reach the critical placement concurrently. At failure, some tire ridges are displacing upwards

while others are moving downward, resulting in the small vertical deformations measured for the tire bale. The individual deformations of the tire ridges could not be measured due to the inability to place instrumentation along the interface.

REMARKS ON THE SIMPLIFIED INTERFACE MODEL

Although the proper design of the tire bale structure can be accomplished with the footprint interface model, a more detailed model was required to quantify the characteristics along the interface controlling the strength of the structure. The simplified interface was developed to model the three-dimensional geometric parameters of the tire bale surface that controlled the interface strength measured during the large scale direct shear testing. Three parameters were needed to model the interface, the inclination of the tire contact surfaces, the actual contact area along the interface, and the initial opening of the interface. The parameters were similar to the geometric parameters describing a generic rock fracture.

An analysis was presented in the following paper in which the three simplified interface parameters were quantified utilizing data collected during the large scale testing of a dry tire bale structure. The simplified interface model was also used, in conjunction with additional laboratory testing, to quantify the influence of different interface conditions (presence of moisture and soil infill), different tire bale structures, and different tire bale geometries on the interface strength which was not presented in the paper. The model was a useful tool in determining how the design of the tire bale structures could be altered to improve the behavior of the structure. The model was also useful in determining how different design considerations must be taken into account in design of the tire bale structures without the need for additional large scale tire bale testing. The simplified interface model was also modified and used to model the vertical deformations of the tire bale structure associated with the applied vertical stresses. The simplified interface model was therefore a more useful interface model for determining the characteristics that controlled the mechanical characteristics of the tire bale interface than the footprint interface model, which can only be used to determine the interface stresses.

REFERENCES

LaRocque, C. J. (2005), *Mechanical Properties of Tire Bales*, Masters Thesis, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin.

Winter, M., Watts, G.R., and Johnson, P.E. (2006), "Tyre Bales in Construction." *Published Project Report PPR080,* TRL Limited.

Zornberg, J. G., Christopher, B. R., and LaRocque, C. J. (2004), "Application of Tire Bales in Transportation Projects," *Geotechnical Special Publication, n 127, Proc. of Sessions of the ASCE Civil Engineering Conference and Exposition,* Baltimore, MD, pp. 42 – 60.

Yang, S., Lohnes, R. A., and Kjartanson, B. H. (2002), "Mechanical Properties of Shredded Tires," *Geotechnical Testing Journal,* Vol. 25, No. 1, pp. 44-52.