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ANALYSIS OF AREAS OF UNBONDED STUCCO USING PLATE MECHANICS

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ABSTRACT

In direct-applied stucco applications, the bond both between the stucco and the substrate, as well as that between individual stucco coats, is of paramount importance for reasons of both durability and life-safety. Prescriptive methods of achieving bond are provided in code-mandated standards and are well documented within the industry. However, direct-applied stucco is a field-applied material that is highly sensitive to substrate preparation, workmanship, and environmental conditions. Because of the myriad factors that can influence bond, the expectation to achieve full bond over an entire building is likely unattainable. Small, localized areas of unbonded stucco typically would not be considered significant enough to justify repair or recladding, but where larger areas of unbonded stucco are found, the decision-making may not be so straightforward. Because the costs of either repairing or recladding a building can be significant, it is imperative that a way of determining whether an unbonded area of stucco is of sufficient size to necessitate such action. This paper presents a method for determining the maximum acceptable size of an unbonded area of stucco. The method involves calculation of an applied bending stress for the unbonded area under code-prescribed design loads using plate mechanics. An allowable bending stress is determined based on the stucco modulus of rupture and a site-specific safety factor.

KEYWORDS: *analysis, bond, direct-applied stucco, plate mechanics, stucco*

INTRODUCTION

Stucco has been used for centuries as a decorative finish over substrates that are insensitive to water, such as stone and clay masonry. Direct-applied stucco (i.e., stucco applied over solid substrates), however, has been the subject of numerous litigation claims because of questions regarding bond.

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Methods of achieving bond, either through mechanical or chemical means, are well-known within the design and construction industry and are provided in ASTM C926. The method(s) by which to measure and evaluate the bond between stucco coats or between stucco and the substrate have not been defined within the industry and are beyond the scope of this research. However, it is noteworthy that a test method to measure bond strength is in development within the ASTM C11.02 subcommittee. It is the intent of this paper to describe methods by which areas of stucco that have been identified as unbonded may be evaluated for safety. (For purposes of this paper, unbonded shall be used to describe stucco with no bond. No discrimination is made between lack of bond either between stucco coats or between the stucco base coat and the substrate).

The approach offered in this research models unbonded stucco as a plate supported along its perimeter edges. Using plate mechanics and code-prescribed lateral design loads, resultant stresses can be computed and compared to an allowable stress based on the modulus of rupture. Ultimately, this analysis can be used to render judgement on the extent of allowable unbonded area for direct-applied stucco applications.

ANALYSIS METHOD

An unbonded area of direct-applied stucco is unlikely to result in damage or life-safety concerns as long as it remains continuous with surrounding well-bonded areas of stucco such that stresses can be transferred between unbonded and well-bonded regions. An issue would only arise if the applied loading exceeded the bending capacity of the stucco, resulting in cracks along the boundaries of the unbonded area. In this condition, the cracks would act as hinges, rendering the unbonded area unable to transfer stresses to the well-bonded area. To whether this is likely to occur and the unbonded area should be repaired, the following steps should be performed:

1. Perform testing to locate and determine size and boundary conditions of unbonded stucco areas. If possible, remove specimens from unbonded areas for laboratory testing.
2. Perform testing in accordance with either ASTM C78/C78M [1] or ASTM C293/C293M [2] (depending on the size and geometry of the sample) to determine modulus of rupture (MOR).
3. Determine the lateral loading as prescribed by code.
4. Analyze the unbonded area under code-prescribed loading using plate mechanics to determine bending stress.
5. Select a suitable safety factor.
6. Compare the bending stress induced by the applied loading to the MOR taking into account the selected safety factor to determine whether repairs should be performed.

Locate and Determine Size and Boundary Conditions of Unbonded Stucco

In order to model the extent of the delamination, the confines of the area must first be identified. Mechanical sounding is a common approach to detection of unbonded areas. Similar in nature to chain drags that are used to identify delaminated concrete decks, the tapping or dragging of a metal object such as a hammer across the surface of a stucco wall will yield different tones between well-bonded and unbonded areas. Well-bonded stucco will give a ringing tone whereas unbonded stucco will give a hollow tone.

Areas of unbonded stucco tend to be circular to amorphous in shape. For ease of analysis, a rectangular area encompassing the unbonded stucco should be assumed.

Where the unbonded area is surrounded on all sides by well-adhered stucco, the boundary conditions are assumed to be fixed along all edges. Where one or more sides of the unbonded area are bordered by a termination (e.g., an expansion joint or similar), those edges may conservatively be considered unrestrained (i.e., free to rotate and displace).

Modulus of Rupture

Unlike its concrete or masonry counterparts, there are no established equations to calculate stucco MOR. A wide range of values for stucco MOR have been presented in the literature. In 1920, Flick [3] stated that portland cement stuccos could be expected to have an average MOR of approximately 2 to 2-1/2 times the tensile strength at 30-days age. The tensile strength reportedly could be expected to be approximately 0.69 MPa (100 psi), indicating that a typical MOR for portland cement stucco would be approximately 1.38 MPa (200 psi) to 1.72 MPa (250 psi).

More recently, Lerner and Donahue [4] performed testing in accordance with ASTM C293 on 6 laboratory-mixed portland cement-lime stucco specimens. The specimens were fabricated using a ratio of 1 part proprietary portland cement-lime stucco mix to 3 parts sand. The average MOR was 1.41 MPa (204 psi) with a coefficient of variation of 14%. This average MOR value correlated well with that reported by Flick, while the low coefficient of variation is attributable to the fact that specimens were prepared in a laboratory environment under optimum controlled conditions.

Innocenzi and Whitlock [5] performed testing in accordance with ASTM C78 on 11 field-sampled proprietary fiber-reinforced plaster (FRP) specimens. They determined that the FRP had an average MOR of 2.80 MPa (406 psi) with a coefficient of variation of 45%. The MOR of FRP is higher than conventional portland cement-lime stucco likely due to proprietary additives and the addition of fibers which are known provide enhanced resistance to tensile-induced cracking. In the authors' experience, the coefficient of variation is typical of field-mixed and field-cured stucco.

Because stucco typically is a field-mixed, hand-applied material, its structural properties may vary significantly. To obtain accurate results, specimens sampled from the project should be tested to determine a site-specific MOR and attendant coefficient of variation.

Lateral Loads
Lateral loading should be determined in accordance with the applicable model building code. In most locations, wind loading will control the design with respect to stucco bond. Substrates for direct-applied stucco, such as concrete and clay masonry, often perform as air barriers (as described in Section C402.5.1.2.1 of the International Energy Conservation Code [6]) and will not permit passage of interior air to the inboard (back) surface of the stucco. Leeward exterior wind pressures will apply tensile loading to the stucco, while interior pressures will tend to "push" the substrate into the stucco. For such substrates, wind loads generally should be calculated assuming no interior pressurization.

Plate Analysis
Timoshenko and Woinowsky-Krieger [7] developed a series of equations and charts to quickly estimate bending moments for uniformly loaded rectangular plates with various boundary conditions. Bending moments are dependent on the boundary conditions, width to length ratio of the plate edge dimensions (i.e., aspect ratio), applied load, and lesser of the plate's length or width. Two common sets of boundary conditions are illustrated in Figure 1.

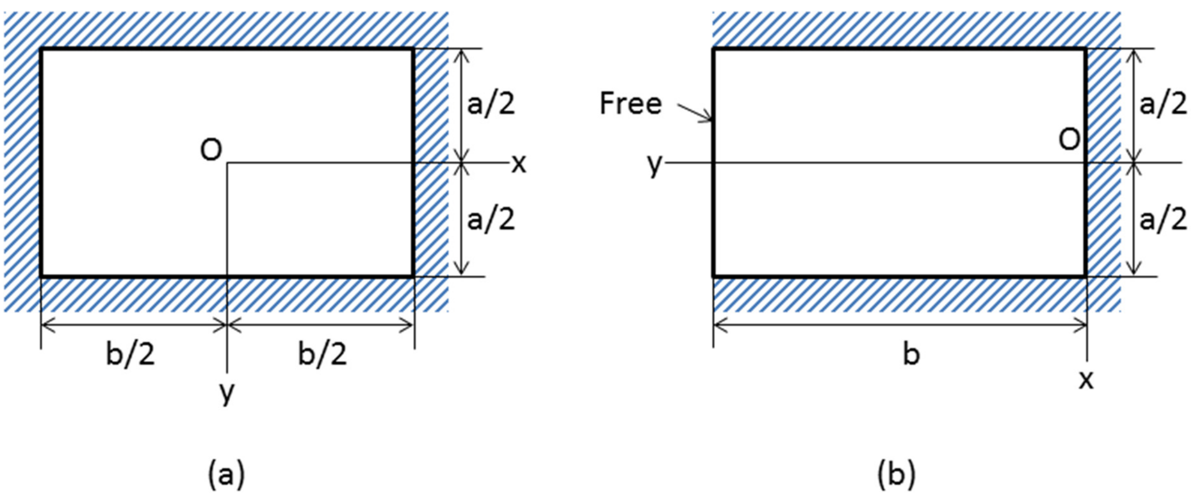

Figure 1: Common Boundary Conditions – Fixed Along All Four Edges (a) and Free Along One Edge and Fixed Along Three Edges (b)

Where the unbonded stucco is continuous with well-bonded stucco along all four edges (as depicted in Figure 1a), the longer side has length *b* and the shorter side has length *a* (i.e., $b \geq a$) and the origin, O, of the x- and y-axes is located in the center of the plate. The maximum moment will occur at the midpoint of the long edge ($x = a/2$, $y = 0$).

At locations where one edge of the stucco is free and the other three edges are fixed (as depicted in Figure 1b), the free edge has length *a* and the edge perpendicular to the free edge has length *b*. The origin is located at the midpoint of the fixed edge opposite of the free edge. The maximum moment will occur at the intersection of the free edge with the fixed edge ($x = a/2$, $y = b$).

For either set of boundary conditions, the maximum unit moment due to the applied load, M_x, is calculated using Equation 1.

$$M_x = \gamma q a^2 \tag{1}$$

The applied uniform load is q, while a corresponds to length as shown in Figure 1. The coefficient γ is a function of the aspect ratio of the plate edges and the boundary conditions as shown in Table 1.

Table 1: Moment Coefficients

Aspect Ratio of Plate Edges (b/a)	**γ for Each Set of Boundary Conditions**	
	Fixed Along All Edges (Figure 1a)	**Fixed Along 3 Edges, Free Along 1 Edge (Figure 1b)**
0.6	N/A	-0.0745
0.7	N/A	-0.0782
0.8	N/A	-0.0812
0.9	N/A	-0.0836
1.0	-0.0513	-0.0853
1.1	-0.0581	NP
1.2	-0.0639	NP
1.25	NP	-0.0867
1.3	-0.0687	NP
1.4	-0.0726	NP
1.5	-0.0757	-0.0842
1.6	-0.0780	NP
1.7	-0.0799	NP
1.8	-0.0812	NP
1.9	-0.0822	NP
2.0	-0.0829	NP
∞	-0.0833	NP

Table Notes: N/A = Not Applicable because b ≥ a in plates fixed along all edges; NP = Not Provided

The unit section modulus, S, is determined based on the thickness, t, of the stucco using Equation 2.

$$S = \frac{1}{6} t^2 \tag{2}$$

The bending stress in the section due to the applied loads, f_b, is calculated using Equation 3.

$$f_b = {}^{M_x}/_{S} \tag{3}$$

Safety Factor

The allowable stress design (ASD) methodology was selected as the basis for analyzing the stucco area. A suitable safety factor can be selected taking into consideration the high degree of variability inherent in a field-applied material like stucco. Aguirre et al. [8] described a method for determining a site-specific safety factor for direct-applied stucco based on the following assumptions:

- Log-normal distribution
- Deterministic applied load (i.e., the applied load is chosen to be conservatively high and with no variation)
- Probability of failure of approximately 1 in 100,000

This probability of failure was selected based on both the nature of the failure mode and the severity of the consequences upon failure. For example, failures that are ductile in nature that would result in less severe consequences may support the selection of a lower probability of failure. According to Section C2.3.6 of ASCE 7-10 [9], current design codes generally use a safety index corresponding to a probability of failure of 1 in 100,000 for materials with a brittle failure mode with a significant severity of consequences. While the failure of an unbonded area of stucco would be brittle in nature, it would not necessarily represent a high severity of consequence, such as would occur with the failure of a main load-supporting structural member. As such, the assumed probability of failure of 1 in 100,000 is conservative and appropriate for stucco finishes.

The site-specific safety factor, Ω, taking into account the coefficient of variation in the MOR determined through testing, $\rho_{\bar{R}}$, is calculated using Equation 4.

$$\Omega = \sqrt{1 + \rho_{\bar{R}}^2}\, e^{4.265\sqrt{\ln\left(1+\rho_{\bar{R}}^2\right)}} \tag{4}$$

Determine Whether Repairs Should Be Performed

To determine whether repairs should be performed, the allowable bending stress value, F_b, is determined using Equation 5, where f_r is the average MOR determined through testing.

$$F_b = {}^{f_r}\!/_{\Omega} \tag{5}$$

Where the f_b calculated for a specific unbonded area exceeds F_b, that area should be repaired.

SAMPLE CALCULATION

For purposes of analysis, a hypothetical stucco-clad building was considered with the following parameters:

- Controlling lateral design load consisting of 4.79 kPa (100 psf) leeward wind

- Average MOR of 1.38 MPa (200 psi) determined through testing with a coefficient of variation of 45%
- Unbonded stucco area measuring 0.30 m (1 ft) by 0.61 m (2 ft) surrounded on all sides by well-bonded stucco
- Stucco thickness of 1.59 cm (5/8 in.)

From Table 1, for a plate that is fixed along all of its edges with b/a = 2.0, γ = -0.0829. Using Equation 1, the maximum unit bending moment is found to be 36.89 N-m/m (8.29 lb-ft/ft). From Equation 2, the unit section modulus is calculated as 0.42 cm^3/cm (0.065 $in^3/in.$). Substituting these results into Equation 3 yields an applied bending stress of 0.88 MPa (127 psi).

To determine the allowable bending stress, a site-specific safety factor is calculated using the coefficient of variation determined by MOR testing in Equation 4, yielding a safety factor of 6.8. From Equation 5, the allowable bending stress is 0.20 MPa (29 psi), significantly less than the applied bending stress under design loads.

Based on this result, the unbonded area has a greater than 1 in 100,000 chance of cracking and spalling off the building during a design wind event. This unbonded area should be repaired.

SUMMARY AND CONCLUSIONS

High-rise construction is subject to significant code-prescribed wind loads, especially in hurricane prone regions of the United States. Direct-applied stucco is a common and popular cladding material selected for this type of construction, particularly in the southeastern and Gulf regions of the United States. Although direct-applied stucco has been used successfully for centuries, over the past 25 years it has been subjected to applications and loads to which it was never formerly exposed.

Because stucco is a field-applied material, it is reasonable to expect small, isolated areas where the stucco is unbonded. Loads that induce stresses that exceed the stucco's MOR can cause cracking around the perimeter of the unbonded area. In turn, the unbonded stucco can become released from its supports and present a life safety risk of falling debris.

This paper offers a technique to analyze unbonded stucco via plate mechanics. Given the dimensions and boundary conditions of the area in question, unit moments can be determined using a series of equations and charts developed by Timoshenko and Woinowsky-Krieger [7]. Associated bending stresses can be calculated by dividing the bending moment by the section modulus which, in turn, is a function of the stucco thickness.

To evaluate the adequacy of the unbonded stucco, the calculated bending stresses are compared to the allowable stress which, in turn, is calculated by dividing the stucco MOR by a site specific safety factor. The MOR is based on laboratory testing of site-specific stucco samples, while the safety factor is based on a statistical analysis of those test results. Stucco areas in which the actual stresses are less than the allowable stress can be deemed adequate, while those exceeding the allowable stress would warrant repair.

This method of analyzing unbonded stucco has not been verified by field or laboratory testing, nor does a standard test method currently exist to perform such testing. However, the aforementioned new test method for field measurement of bond strength of stucco by direct tension is currently in development by ASTM Committee C11 on Gypsum and Related Building Materials and Systems, Subcommittee C11.02 on Specifications and Test Methods for Accessories and Related Products [10]. Proof load testing of unbonded areas could be performed in accordance with this proposed standard test method to verify results of the plate mechanics analysis technique.

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