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UNSTABLE, 2D DEBONDING IN SANDWICH-LIKE TILING SYSTEMS

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1. INTRODUCTION, MOTIVATION, AND OBJECTIVES

Tiling systems have been used by builders since ancient times, serving functional, structural, and aesthetic purposes as building cladding, floors, walls, and roofs coverings, artwork, mosaics, and more. In recent decades, along with their traditional uses, they have found growing application as thermal barriers systems in space-crafts and nuclear facilities [1, 2]. They have also been increasingly used for building facade cladding, due to the increase in high-rise building on the one hand, and their relatively low maintenance costs on the other.

As is typically the case in adhesively bonded sandwich plate structures, interfacial debonding is among the main failure mechanisms of tiling systems. In mild cases, interfacial damage may be limited and go unnoticed for quite some time. However, in more severe cases, interfacial debonding may propagate, leading to the detachment of the tile from its substrate and to its eventual falling. Falling of thermal barriers tiles from the space shuttle Columbia in the year 2003 led to its catastrophic disintegration and the death of all 13 astronauts upon reentry into the Earth's atmosphere [3]. Falling of tiles from building facedes on bystanders is another cause of injuries and death [4].

The main causes of interfacial debonding damage in tiling systems, which is *the* precondition for the eventual falling of tiles, are hygro-thermal effects. Exposure to large thermal differentials cycles, as well as to moisture and drying cycles, causes differential shrinkage of the constituent layers. This differential shrinkage results in interfacial traction concentrations, which, in turn, drive the interfacial debonding mechanisms.

Considering the extensive and increasing use of tiling systems on the one hand and the possible grave consequences of their failure on the other, understanding the evolution of interfacial debonding mechanisms is indispensable in the design of this ubiquitous layered structural form. Essential questions that arise in this regard are: What are the hygro-thermal loading levels under which interfacial damage begins to accumulate in a given tiling system? How does the two-dimensional (2D) debonding region change in size, location, and shape as the load levels increase? Is the growth of interfacial damage a stable process or an unstable one? How do the tile's geometry, the interfacial parameters, and the substrate's boundary conditions affect the debonding mechanism's evolution? The focus of the present paper is to help shed new light on and gain new insight into these pertinent questions.

The main challenges in addressing the raised questions regarding the evolution of interfacial debonding mechanisms in tiling systems are due to their salient physical features, the three most notable of them being:

1. A relatively soft adhesive mortar layer is sandwiched between two much more rigid substrate and tile layers;
2. The interfacial interactions that drive the debonding mechanism are governed by a small length scale while a much larger length scale defines the layered system's lineal dimensions; and
3. The interfacial tractions in this layered plate problem are 3D while the debonding region's evolution is 2D and geometrically irregular by nature.

2. METHODOLOGY

Specially tailored analytical and computational tools are developed in the present paper to address the salient physical features and to explore the nature of the problem at hand. Their totality comprises an analytical computational platform which includes a multilayered plate theory, and a corresponding triangular finite element (FE). To capture the high stress and deformation gradients in the soft adhesive mortar layer and the interfacial tractions at its interfaces, the formulation adopts the extended high-order plate theory for that layer [5,6,7]. Other specially tailored methodologies included in the formulation are plate-like cohesive interfaces to capture the 3D nature of the interfacial interactions, a pseudo arc-length procedure to explore the stability features of the debonding process, and a mode decomposition procedure to alleviate shear locking in the triangular FE [8,9,10].

3. NUMERICAL EXAMPLE

The numerical example focuses on the triggering and evolution of interfacial debonding in single tile configurations under uniform heating [9]. These simple conditions allow studying the problem in pure form and are therefore conducive to shedding light on the fundamental nature of the debonding mechanisms in this structural context. Emphasis is placed on the effects of different tile geometries, interfacial properties, and substrate boundary conditions on the geometrically irregular nature and the stability characteristics of the debonding mechanism. More details are given in [9].

Fig. 1 shows the configuration of Case A - a 200mm and 20mm thick square tile, connected by a 10mm thick adhesive mortar layer to a 200mm thick substrate layer. The three layers are subjected to a uniformly distributed heating differential Δθ. Taking advantage of the double symmetry conditions, only the upper tight quadrant is analyzed, see Fig. 1(c).

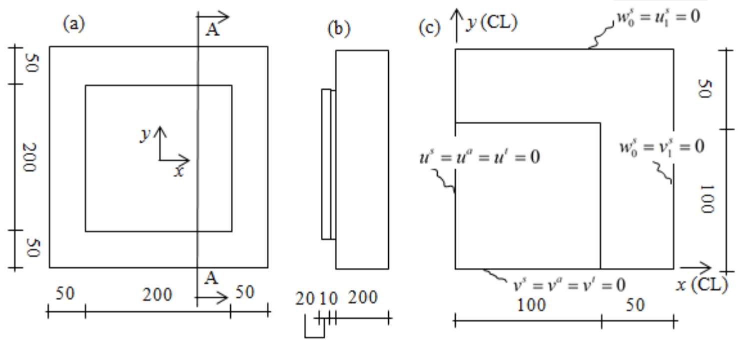

Fig. 1: Configuration of a square tile – Case A (a) plan; (b) cross-section AA; and (c) analyzed quadrant and the double symmetry boundary conditions (adapted from [9] with permission from Elsevier).

The evolution of the debonded area as a function of the temperature differential Δθ is depicted in Fig. 2. Fig. 2 can be thought of a type of "equilibrium" path, showing the normalized debonded area (debonded area divided by originally bonded area) A_d against Δθ. Capturing the non-monotonous and highly irregular behavior in Fig. 2 is made possible through the use of the pseudo arc-length procedure. It can be seen that up to Point A1, at approximately 55°C, only negligible debonding occurs. From Point A1 to Point A2, the debonding process becomes much more "rapid", until a snap occur between Points A2 and A3. This zoom-in on the snap region, indicated by dashed lines, reveals an increase of debonded area without increase in thermal load. This type of behavior signifies an unstable nature of the debonding mechanism. The corresponding thermal load $\Delta\theta_{snap}$=75.53°C, well within service conditions in some cases, can therefore be considered as the debonding failure load of the layered system. The subsequent stabilization between Points A3 and A4 can be explained as an artificial product of the quasi-static analysis and is not very significant from a physical stand point.

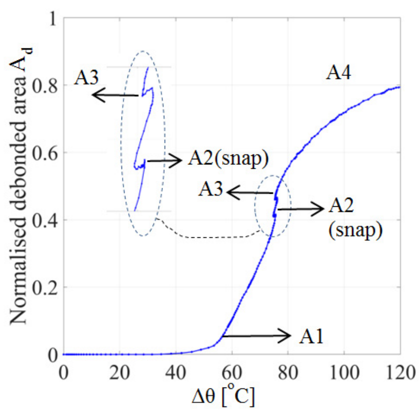

Fig. 2: Equilibrium path of case A: Normalized debonded area A_d Vs. the temperature differential Δθ (adapted from [9] with permission from Elsevier).

The geometrically irregular evolution of the debonding mechanism described in Fig. 2 is depicted in Fig. 3. Fig. 3 shows the progression of the debonding front, which is represented by the contour maps of the interfacial peeling traction at the substrate-adhesive interface. Figs. 3a-d show snap-shots of the debonding fronts that correspond to Points A1-A4, defined in Fig. 2 and referred to above. It can be seen that the debonding starts at the corner of the tile (Fig. 3(a)) and later propagates towards its center. The evolution in debonded area corresponding to the snap region between Points A2 and A3, is shown in Fig. 3(b) and 3(c). It seems that the snap is associated with a debonding front coalescence from the adjacent left and bottom quadrants (not shown in the figure). This suggests that the unstable nature of the mechanism is associated with the geometrical nature of the debonding area. At the end of the process, Fig. 3(d), the remaining bonded region becomes circular.

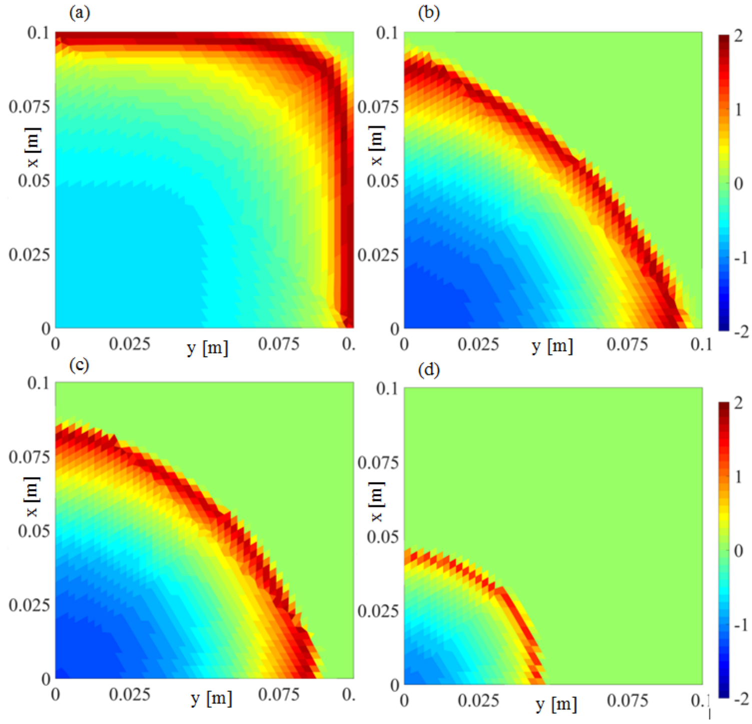

Fig. 3: debonding fronts: (a) Point A1; (b) Point A2; (c) Point A3; and (d) Point A4; (reprint from [9] with permission from Elsevier).

4. SUMMARY AND CONCLUSIONS

The numerical study reveals the unstable and the geometrically irregular nature of debonding mechanisms in tiling system. As is shown in the full paper, this observation is quite general as it applies to a wide range of tile geometries, boundary conditions, and interfacial properties. Understanding that instabilities are an inherent characteristic in the debonding mechanism is significant, especially because this aspect of the structural response is often overlooked in the design phase. Differently from other approaches, the present paper focuses directly on the 2D evolution of the debonding mechanism and on its relation to the observed instabilities.

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