

On the loads driving tile detachments

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Abstract

Tile detachment from building façades is mainly due to debonding mechanisms triggered by hygrothermal effects. Yet, the hygrothermal loading modes that drive these mechanisms have not been clearly identified, and hygrothermal loads are commonly described directly by heat and moisture fluctuations, which obscures their structural-mechanics implications. This paper addresses both gaps. First, we propose the differential free strain at the interfaces — the vector of differences between the free strains of adjacent layers — as the structural language for hygrothermal loads: a dimensionless measure that maps many hygrothermal states onto one structural response and removes the ambiguity of heating and cooling. Second, we use it to order the hygrothermal loading space into six basic modes: uniform expansion or contraction of the substrate, the adhesive, or the tile. Third, we show, by a kinematic argument at the tile corners and a nonlinear cohesive finite-element model, that only two of them drive debonding — tile shrinkage and substrate expansion, the two modes whose DFSI has a single positive entry — whereas their reverses stop it and the adhesive modes are essentially neutral. Fourth, we show that this selection holds across a 384-case factorial of layer moduli, thicknesses, tile size, and aspect ratio, for tiles bonded to substrates much stiffer in bending than the tile, such as concrete and masonry walls: in every case, the sign of the governing corner peeling traction is preserved. The two drivers coincide with those identified independently in field surveys of detached tiles.

Keywords — Interfacial debonding, Differential free strain, Cohesive interface, Hygrothermal loading, Adhesively bonded tiles, Tile detachment, facade failure.

1 Introduction

1.1 Background and motivation

Tile detachment from building façades is among the most common and the most hazardous façade failures. Tiles that debond and fall endanger passers-by, and their repair is costly and disruptive (Ho et al. 2005; Bauer et al. 2011; Beasley 2013; Gaspar 2017; Bauer & Souza 2022; Chew et al. 2025).

A bonded tiling system is comprised of the tile, the substrate, which is typically much stiffer in bending than the tile, and the adhesive layer that joins them. Development of debonding failures at the substrate-adhesive interface and/or adhesive-tile interface in such a system is a necessary, and often sufficient, condition for tile detachment and potential fall (Zurbriggen & Herwegh 2016; Jenni et al. 2005, and Wetzel et al. 2012a, Wetzel et al. 2012b, Feldfogel & Rabinovitch 2018b, Feldfogel & Rabinovitch 2021, Lovinger 2002, Lovinger et al. 2001). Understanding debonding mechanisms is therefore a prerequisite for informed design and analysis of bonded tilings systems.

It is well established that hygrothermal effects are, by far, the main type of load driving debonding mechanisms in building tiles (Mahaboonpachai et al. 2008; Wetzel et al. 2010; Wetzel et al. 2012a; Wetzel et al. 2012b). Exposure to heat and moisture gradients, combined with differential expansion coefficients of the layers of the tiling system, results in interfacial shear and peeling tractions. Under constant exposure to daily and seasonal hygrothermal variations, these tractions can reach critical values that drive debonding mechanisms, and eventually, tile detachments. Field studies reinforce this notion. Combining a survey of outdoor tilings with numerical modeling, Zurbriggen and Herwegh (2016) attribute observed detachments to specific hygrothermal actions, underscoring that identifying which loadings drive debonding is central.

The difficulty lies in the loads themselves. The hygrothermal loading of a tiling is a jungle: temperature and moisture vary in time, through the thickness, and over the plane of every layer, as functions of climate, season, orientation, exposure, and the materials and geometry of the layers. Every such state acts through the expansion coefficients of the layers, and the same state is described in different studies by temperatures, by moisture contents, or by the shrinkage of a single layer (e.g., temperatures in Zurbriggen & Herwegh 2016; moisture transport in Wetzel et al. 2012a; the shrinkage of a single layer in Herwegh et al. 2015 and Feldfogel & Rabinovitch 2018b). Without a common language and a finite set of reference

loadings, results obtained for one loading can neither be compared with, nor transferred to, another. A common frame in which different loadings can be categorized, compared, and evaluated is called for.

Some indications of the exact hygrothermal conditions driving debonding do exist. Field surveys point to thermal shrinkage of the tiles and hygric swelling of the substrate (Zurbriggen & Herwegh 2016). Numerical studies have followed shrinkage of the tile or of the adhesive (Herwegh et al. 2015; Feldfogel & Rabinovitch 2018b, 2026). Yet, these indications are sporadic, case-by-case, and they lack of a mechanically-based rationale for why certain hygrothermal loads drive debonding, and others do not.

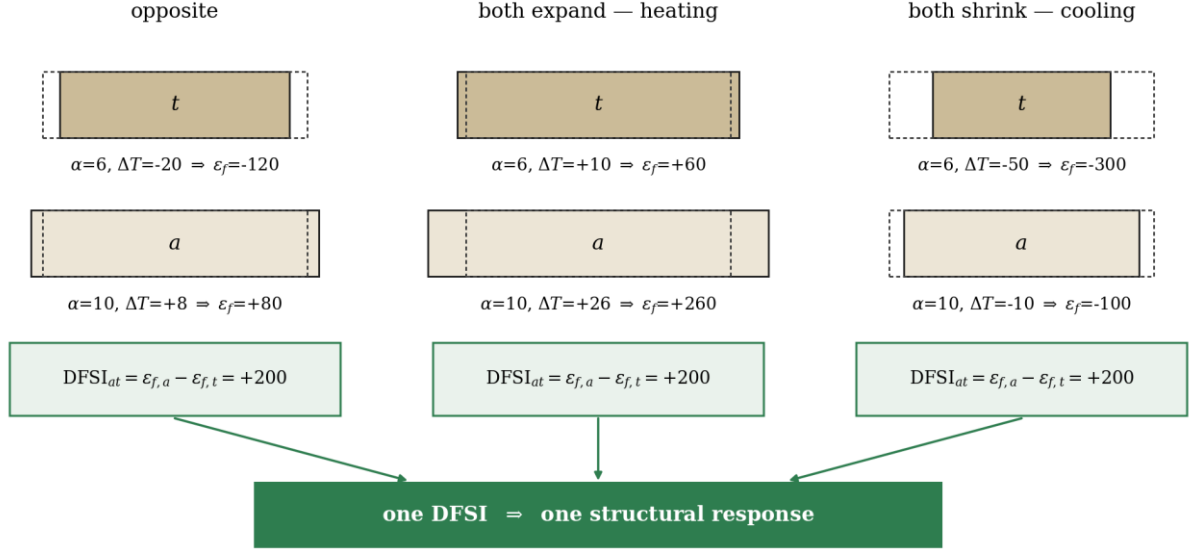
Two needs therefore remain unmet. The first, and foremost, is a clear identification of the loads that drive tile detachment, one that is grounded in mechanics and shown to hold across the range of realistic tiling configurations, rather than inferred case by case. The second is a common conceptual framework and structural language in which hygrothermal loads can be better expressed, classified, and understood from a structural mechanics perspective. The main objective of this study is to bridge these gaps. This includes defining a structural-mechanics-based conceptual framework, model, and terminology for debonding-associated hygrothermal effects, identifying the essential debonding-driving loading modes and explaining them within this framework, and demonstrating that this identification, and by extension the conceptual framework underlying it, hold across a wide parametric range relevant to building applications.

Section 2 introduces the structural-mechanics-based conceptual framework and methodology for the investigation of debonding-driving hygrothermal loads. Section 3 carries out the numerical investigation of the essential debonding driving loads across the parametric campaign. Section 4 summarizes the findings.

2 Conceptual framework and methodology

We first set the framework and terminology in which we express hygrothermal loads (Section 2.1), then order the loading space into six basic modes (Section 2.2), and pose a heuristic hypothesis on which of them drive debonding based on a simple structural model (Section 2.3). The assumptions underlying our study and the limitations of its application (Section 2.4) and the numerical model used in this study (Section 2.5) follow.

2.1 The differential free strain at the interfaces (DFSI)



α in $10^{-6}/^\circ\text{C}$, ΔT in $^\circ\text{C}$, strains in $\mu\epsilon$; dashed = undeformed, solid = free-deformed (elongations $\times 1100$, one scale throughout)

Fig. 1. The DFSI as the language of hygrothermal loads. Three different thermal loadings of a tile (t) over an adhesive (a) — opposing, both expanding (heating), and both shrinking (cooling) — impose the same DFSI at the adhesive–tile interface, $DFSI_{at} = \varepsilon_{f,a} - \varepsilon_{f,t} = +200 \mu\epsilon$, and hence the same structural response. Representative expansion coefficients; dashed, undeformed; solid, free-deformed, at one magnification throughout.

To represent and study the debonding-driving aspect of hygrothermal effects, we use the differential free strains at the interfaces (DFSI), rather than thermal or moisture differentials, as the representative parameter. We define DFSI as the differential strains that would develop across the interfaces of the bonded tiling system if the layers were free to expand, that is, not restrained by adjacent layers and/or supports of any kind. More concretely, DFSI is defined as a point-wise field over each of the two physical interfaces, namely the free strain of the lower layer minus that of the upper one, $DFSI_{sa} = \varepsilon_{f,s} - \varepsilon_{f,a}$ at the substrate–adhesive (sa) interface and $DFSI_{at} = \varepsilon_{f,a} - \varepsilon_{f,t}$ at the adhesive–tile (at) interface. A positive DFSI means that the lower layer tends to expand relative to the upper one. In the tri-layered system, the DFSI at a point of the plane is thus the two-entry vector $DFSI = [DFSI_{sa}; DFSI_{at}]$; a system of n layers would have $n - 1$ entries.

The choice of DFSI to describe and study hygrothermally-induced debonding is explained next. Structurally, debonding is not dictated directly by hygrothermal effects, but rather by the differential free displacements across the interfaces it tends to produce; these differential interface displacements cause interfacial tractions which in turn drive debonding

mechanisms. Therefore, it does not matter which combination of heating, cooling, wetting and drying, acting through which expansion coefficients produced a given state of differential free displacements; what matters is only their magnitude and distribution across the interfaces. Taking the differential free displacements across the interface as a loading parameter is, however, problematic. They depend on configuration-specific displacement constraints (boundary conditions) and are not uniquely defined by the given set of hygrothermal conditions and expansion coefficients causing them. As such, they constitute a hybrid of a loading condition (vis-a-vis the hygrothermal conditions) and a response parameter (vis-à-vis their dependence on the boundary condition). In contrast, the differential free strains DFSI, which are the derivatives of the differential free displacements, *are* uniquely defined for a given set of hygrothermal conditions and expansion coefficients, they don't depend on displacement boundary conditions, and as such they are a more natural measure of hygrothermal loading.

For DFSI to be a sound measure of debonding-inducing hygrothermal loads, it should correlate linearly to the relative free displacements which govern the debonding process. This requires that the effect of displacement boundary conditions on the differential free displacements be neutralized (recall that the relative free displacements are integrals of the DFSI). This condition occurs, e.g., when a common displacement constraint applies at the same point to all the bonded layers, which is the solution affected in this study, see Section 3. The challenge of handling this “integration constant” difference between the differential free displacements and the DFSI in more general cases is identified here and designated for future research.

Expressing the hygrothermal loading through the DFSI is advantageous because it reduces the former. The map from the hygrothermal state to the DFSI is many-to-one: different combinations of hygrothermal fields and expansion coefficients can produce the same DFSI, whereas different DFSI necessarily stem from different fields or coefficients. Fig. 1 shows three thermal loadings of a tile–adhesive pair — opposing, heating, and cooling — that differ in every temperature differential, expansion coefficient, and every free strain, yet impose the same DFSI at the interface, and hence faces the same structural response. The reduction retains exactly the information that reaches the interfaces. It also renders the loading non-dimensional: free strains are dimensionless, whereas temperatures, moisture contents and expansion coefficients are not.

The DFSI carries two further advantageous features in addition to model reduction and non-dimensionalization. First, it prevents misattribution: the heating and cooling cases in Fig. 1 impose the same DFSI and drive the same structural response, so a failure framed in temperatures might be attributed to cooling or to heating, when it was in fact caused by a particular DFSI. Second, the mapping is well posed: a DFSI exists for every hygrothermal state (existence), it is unique for given fields and expansion coefficients (uniqueness), and it changes little when the hygrothermal input changes little (stability). A result expressed in DFSI terms therefore applies to every hygrothermal state that produces it.

2.2 Six basic loading modes

Even in DFSI terms, the loading space remains an unwieldy one. A faithful description of the hygrothermal state is spatiotemporally dynamic and complex. Heat and moisture flow through and along the layers as a function of geography, climate, season, exposure, and the geometry and materials of the layers. Every such state imposes some DFSI, and the set of possible DFSI states is a continuum. To bring order into it, we cast it onto a finite set of fundamental DFSI modes, whose responses can be examined one at a time.

A general DFSI loads both interfaces at once, which clouds the structural reading: neither a given traction state nor a given failure can then be attributed cleanly to either interface. The simplest loadings to examine first are uniform free strains within a single layer. Per unit free strain, their DFSI vectors are: for expansion and contraction of the substrate, $\text{DFSI} = [\pm 1; 0]$, loading the sa interface only; for expansion and shrinkage of the tile, $\text{DFSI} = [0; \mp 1]$, loading the at interface only; and for expansion and contraction of the adhesive, $\text{DFSI} = [\mp 1; \pm 1]$, loading both interfaces with entries of opposite sign that sum to zero. These are the six basic loading modes, Fig. 2. While the interfaces are intact and respond linearly, any uniform loading is a superposition of these six. Together with the DFSI, the six modes reduce the hygrothermal loading space from a continuum of fields to a handful of dimensionless, physically interpretable coordinates.

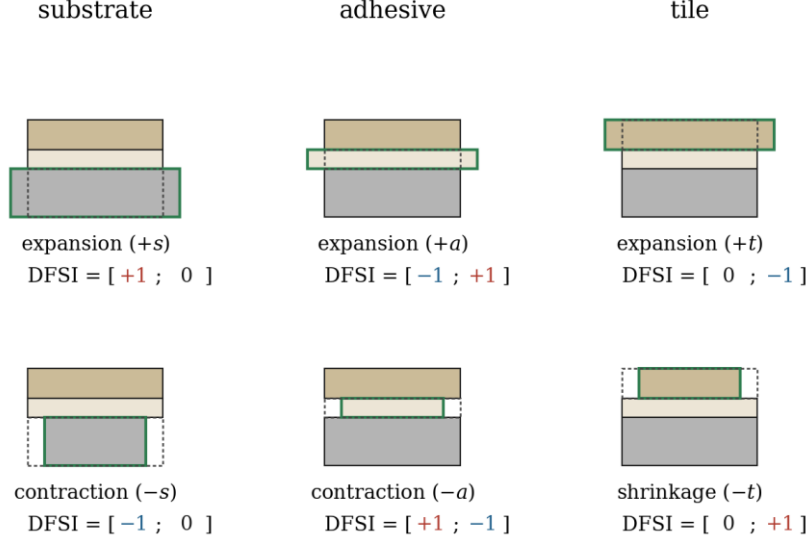


Fig. 2. The six basic loading modes: uniform expansion (+) and contraction (−) of the substrate (*s*), the adhesive (*a*), and the tile (*t*), each with its DFSI vector $[DFSI_{sa}; DFSI_{at}]$ per unit free strain (positive entries in red, negative in blue). The loaded layer is drawn free-deformed against its undeformed length (dashed).

2.3 The hypothesis: two debonding drivers

We hypothesize that only two of the six basic modes drive debonding: uniform shrinkage of the tile and uniform expansion of the substrate. Their reverses, tile expansion and substrate contraction, inhibit debonding, and the two adhesive modes are essentially neutral (inactive) debonding-wise. In DFSI terms, the rule is a sign rule on the DFSI vector: the two drivers are exactly the modes whose DFSI has a single, positive entry — the lower layer expanding relative to the upper one at one interface; the two stoppers are those whose DFSI has a single, negative entry; and the two adhesive modes are those whose DFSI entries have opposite signs and sum to zero. The claim is falsifiable: a stopper that debonds, or a third driver among the six, would break it.

The hypothesis rests on a heuristic kinematic argument at the tile corners, in which the bending of the substrate is neglected relative to that of the adhesive and the tile, see Fig. 3. The argument realistically presumes a substrate much stiffer in bending than the tile and the adhesive. Under tile shrinkage, a tile–adhesive bilayer bends concave up and its corners move away from the substrate; for such a bilayer to be bonded to a rigid substrate (as is the case in the bonded three-layered system), peeling tractions must develop at the corners of the sa interface. Substrate expansion pushes out the bottom of the bilayer and produces the same corner-opening scenario. We therefore refer to these two modes as debonding drivers (DD).

Under the converse modes of tile expansion and substrate contraction, the bilayer bends concave down and its corners bear against the substrate, inhibiting debonding; we refer to them as debonding stoppers (DS).

The adhesive modes rank low because each combines a driver and a stopper. A uniform free strain equal in all three layers is stress-free; subtracting it, adhesive expansion is equivalent to tile shrinkage (a driver) combined with substrate contraction (a stopper), and adhesive contraction to substrate expansion (a driver) combined with tile expansion (a stopper), Fig. 3(b). The opening and closing actions at the corners tend to cancel each other. The cancellation is not exact in general — it relies on the near-equality of the driver and stopper corner tractions — so the adhesive modes are expected to contribute little to debonding rather than nothing, as Section 3.4 quantifies.

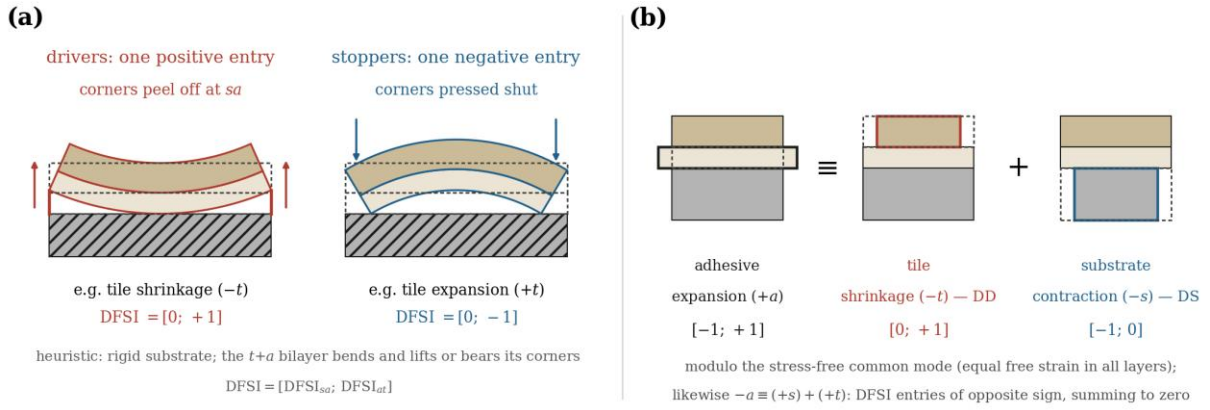


Fig. 3. The kinematic heuristic behind the hypothesis. (a) With the substrate taken as rigid, the free bending of the tile–adhesive bilayer lifts its corners off the sa interface under the drivers, whose DFS_I vector has a single positive entry, and presses them shut under the stoppers, whose DFS_I has a single negative entry; one example of each is drawn. (b) Up to the stress-free common mode, each adhesive mode is the sum of one driver and one stopper, and its DFS_I vector is the sum of theirs; adhesive expansion is drawn.

Interestingly, our hypothesis finds empirical support in the field. Combining a survey of outdoor tilings with numerical modeling, Zurbriggen and Herwegh (2016) related the debonding they observed in micrographs of in-field detachments to a relative expansion of the substrate with respect to the tiles, caused either by hygric swelling of the substrate or by rapid thermal shrinkage of the tiles, as in a summer hailstorm. In fact, they specifically state the combination of tile shrinkage and substrate expansion as the most severe hygrothermal loading condition. Their two field-identified drivers are precisely the two selected here, reached independently and by different means.

2.4 Assumptions and limitations

The reduction and its verification rest on a set of assumptions and associated limitations:

Flexurally rigid substrate. The kinematic heuristic of Section 2.3 takes the substrate as rigid and lets only the tile–adhesive bilayer bend. The results therefore apply to tiles on concrete walls, masonry, and similar massive substrates in which the bending stiffness of the substrate is at least about 580 times larger (the smallest ratio in the parametric campaign of Section 3.5) than that of either the adhesive or the tile. Where the tile is comparable to the substrate in bending stiffness, or stiffer — ceramic tiles on dry-lining boards, for example — the substrate bends with the tile, and the hypothesis is not expected to hold: debonding may migrate from the sa interface, the signs of the corner peeling tractions may flip, and the split into drivers and stoppers need not follow the one established here. Such cases are designated for future work.

Superposition in a nonlinear system. The decomposition of a uniform loading into six basic modes, and the reading of the adhesive modes as the sum of a driver and a stopper, rest on linear superposition. The system is linear only while the interfaces are intact and the cohesive laws remain in their initial, nearly linear range. Once softening and debonding set in, the response to a combination of modes is no longer the sum of the responses to each. The classification is therefore a statement about what triggers debonding, not about the full nonlinear path.

DFSI applicability depends on boundary conditions. As discussed in Section 2.1, for DFSI to be a true proxy of both the hygrothermal effects *and* the debonding-governing differential free displacements requires a shared in-plane displacement constraint at a point for all the bonded layers. While this can be affected rather straight-forwardly in a numerical simulation, it is currently generally applicable in configurations with irregular/complex displacement constraints.

Idealized free strains and loading. The free strains are taken uniform over the plane and through the thickness of each layer, and are applied proportionally, monotonically, and quasi-statically. In-plane gradients — partial shading, drying from the joints — time-dependent behavior of the cementitious adhesive such as creep and relaxation, and the cyclic, daily and seasonal, character of real exposure, with the fatigue and ratcheting it may cause, are not considered.

Interfaces and layers. The layers are linear elastic; cracking within the adhesive or the tile is not modeled. Both the material and interfacial properties are taken independent of temperature and moisture, so that hygrothermal effects enter only through the free strains. The parameters of both interfaces is assumed equal.

Configuration. A single tile is analyzed with free edges, on a substrate extending 50 mm beyond it, using symmetry to reduce the model to an octant. Grout joints, neighboring tiles, and edge restraint, which constrain the tile edges in a tiled field, are not considered in this study.

2.5 Formulation for the numerical test environment

The model is the high-order layered plate model and its specially tailored finite element formulation, detailed and validated in Feldfogel & Rabinovitch (2016, 2018a, 2018b, 2026). It represents the substrate (s), the adhesive (a), and the tile (t) as linear elastic plates with first and high order strains: first-order shear-deformable for the stiffer substrate and tile, third-order for the softer adhesive, joined at the sa and at interfaces by exponential cohesive laws. Only the two ingredients that carry the loading and the failure are restated here: the strain decomposition and the cohesive laws.

The total strains ϵ_i^{tot} are assumed to be additively composed of a stress-related term ϵ_i^{stress} and a stress-free term ϵ_i^{free} , $i = s, a, \text{ or } t$:

$$\epsilon_i^{tot} = \epsilon_i^{free} + \epsilon_i^{stress} \quad (1)$$

The stress-free strains represent the linear expansion in the x, y, z directions when the layers are free to expand, i.e., are unrestrained by adjacent layers or other restrictions. In the context of the present study, they represent isotropic and hydrostatic hygro-thermal effects, the main debonding-inducing driving force in adhesively bonded tiles. The free strains read:

$$\epsilon_s^{free} = \begin{bmatrix} \mathcal{E}_{xx}^{s,free}(z_s) \\ \mathcal{E}_{yy}^{s,free}(z_s) \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \epsilon_a^{free} = \begin{bmatrix} \mathcal{E}_{xx}^{a,free}(z_a) \\ \mathcal{E}_{yy}^{a,free}(z_a) \\ \mathcal{E}_{zz}^{a,free}(z_a) \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad \epsilon_t^{free} = \begin{bmatrix} \mathcal{E}_{xx}^{t,free}(z_t) \\ \mathcal{E}_{yy}^{t,free}(z_t) \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

where ϵ_i^{free} is the strain vector of the i 'th layer ($i=s$ or a or t).

The plate-type exponential cohesive interfaces were developed in Feldfogel & Rabinovitch (2018a) and they read:

$$\begin{aligned}
T_x(x, y) &= 2 \frac{\phi}{(\delta_0)^2} \left(1 + \frac{\Delta w(x, y)}{\delta_0} \right) \exp \left(-\frac{\Delta w(x, y)}{\delta_0} - \frac{(\Delta u(x, y))^2 + (\Delta v(x, y))^2}{(\delta_0)^2} \right) \Delta u(x, y) \\
T_y(x, y) &= 2 \frac{\phi}{(\delta_0)^2} \left(1 + \frac{\Delta w(x, y)}{\delta_0} \right) \exp \left(-\frac{\Delta w(x, y)}{\delta_0} - \frac{(\Delta u(x, y))^2 + (\Delta v(x, y))^2}{(\delta_0)^2} \right) \Delta v(x, y) \\
T_z(x, y) &= \frac{\phi}{(\delta_0)^2} \exp \left(-\frac{\Delta w(x, y)}{\delta_0} - \frac{(\Delta u(x, y))^2 + (\Delta v(x, y))^2}{(\delta_0)^2} \right) \Delta w(x, y)
\end{aligned} \tag{3}$$

$\Delta u(x, y)$, $\Delta v(x, y)$, $\Delta w(x, y)$ are the differential displacements across the interface in the x , y , and z directions, ϕ is the interfacial fracture toughness, and δ_0 is the characteristic interfacial length. Same cohesive laws are attributed to the adhesive-tile interface and the adhesive-substrate interface.

3 Numerical study and discussion

The numerical study is organized as follows: First, we test the six basic modes in a reference configuration, one at a time and each with a unit free strain, identify which of them drives debonding, stops it, or is neutral (Section 3.2), and look into how the debonding kinematics evolves at the failure interface (Section 3.3). We then dive into the structural mechanism underlying the debonding drivers and stoppers, showing the mechanism behind certain modes being debonding drivers, while others are stoppers or neutral (Section 3.4). Finally, we test whether the results found on the reference configurations, including the modes classification and the mechanism rationale underlying it hold across a wide parametric space of tiles on flexurally rigid substrates (Section 3.5).

3.1 Configuration

The basic configuration considered in the numerical study is a 200×200 mm² square porcelain tile adhesively bonded to a concrete substrate, see Fig. 4. The 50 mm peripheral margin between the tile's and the substrate's edges is aimed at neutralizing the effect of substrate boundary conditions. The thicknesses of the substrate, adhesive, and tile layers are 200, 10, and 10 mm, respectively, and their Young's moduli are 30, 4, and 60 GPa, representing typical dimensions used in practice. The bending stiffness of the substrate alone,

proportional to $E h^3$, thus exceeds that of the tile and the adhesive combined by a factor of about 3700 — the rigid-substrate regime presumed by the hypothesis (Section 2.3). The interface parameters are $\phi = 1.36 \cdot 10^{-5} \text{ J/mm}^2$ and $\delta_0 = 0.005 \text{ mm}$ based on the experimental calibration in Feldfogel & Rabinovitch (2021).

Based on symmetry about the x , x' , y , and y' axes, the computational domain is the octant described in Fig. 4(b), together with the boundary conditions therein. In region R1, there is only a substrate layer. In region R2, there are three bonded layers. The finite element mesh is shown in Fig. 4(c). The size of the elements in the entire mesh is 2.5 mm, one-quarter of the thickness of the thinnest layer. Mesh convergence is verified by a coarsening study (10, 5, and 2.5 mm) in Appendix A.

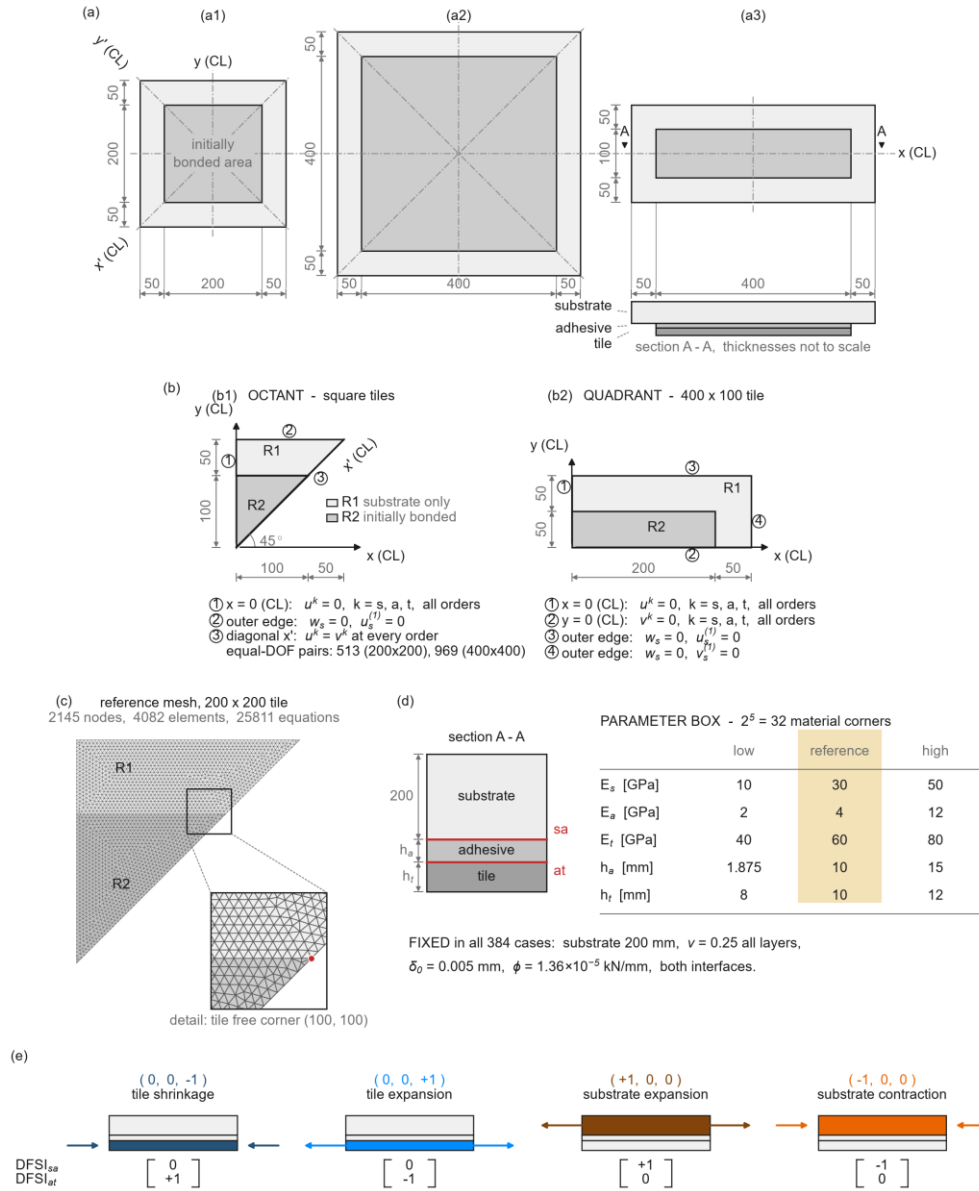


Fig. 4. Configuration of the numerical study. (a) The three tile geometries, each with a 50 mm substrate margin: (a1) the 200×200 mm reference tile, (a2) a 400×400 mm tile, and (a3) a 400×100 mm tile, with section A–A (thicknesses not to scale). (b) Computational domains and boundary conditions: (b1) the octant used for the square tiles and (b2) the quadrant used for the rectangular tile; R1, substrate only; R2, initially bonded. (c) Reference mesh of the 200×200 mm tile, with a detail at the free corner. (d) Section A–A with the sa and at interfaces, and the moduli and thicknesses of the reference set together with the low and high levels of the parametric campaign; the substrate thickness (200 mm), Poisson's ratio (0.25), and the cohesive parameters are fixed throughout. (e) The four driver and stopper modes, with their free-strain vectors (s , a , t) and DFSI vectors $[DFSI_{sa}; DFSI_{at}]$.

The load parameter is the uniform free strain applied to the loaded layer, ε_i ($i = s, a, t$), with the free strains of the two other layers held at zero; for the tile, it is denoted ε_t . In DFSI terms, a free strain of the substrate alone is a DFSI at the sa interface, $DFSI_{sa} = \varepsilon_s$, and one of the tile alone a DFSI at the at interface, $DFSI_{at} = -\varepsilon_t$. It is increased monotonically, and the equilibrium path is traced by an arc-length procedure.

The response is described by the debonded area fraction A_d — the current debonded area divided by the initially bonded area — and by the debonding fronts at the plane of the failing interface.

3.2 The essential loading: from six modes to two

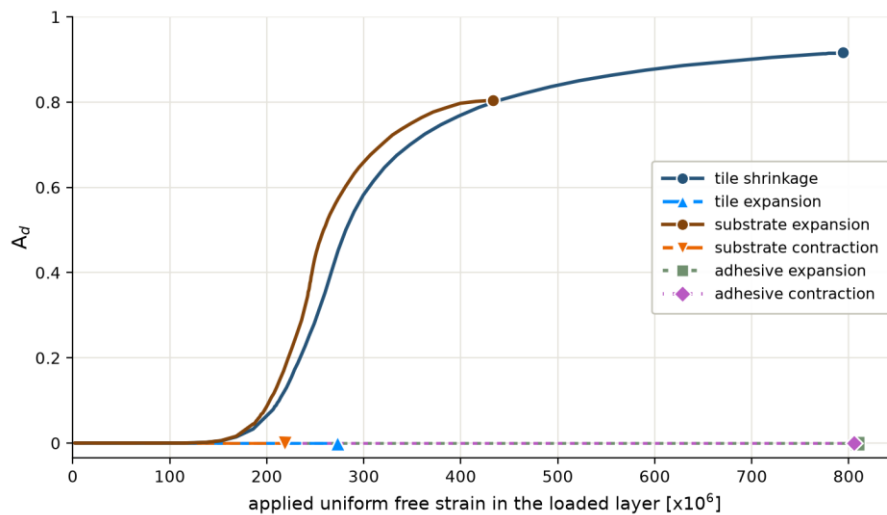


Fig. 5. The six basic modes: debonded area fraction A_d at the sa interface against the uniform free strain applied to the loaded layer. Only tile shrinkage and substrate expansion debond; the other four modes remain

fully bonded ($A_d = 0$) over the whole computed range — their curves coincide on the axis, and the end markers give each run's reach. The two debonding curves are truncated at their peak A_d : 0.92 at $794 \mu\epsilon$ (tile shrinkage) and 0.80 at $433 \mu\epsilon$ (substrate expansion).

Fig. 5 shows the debonding response under the six basic modes. Only tile shrinkage and substrate expansion debond, in accordance with the hypothesis (Section 2.3) and with the field observations of Zurbriggen and Herwegh (2016); in both, debonding occurs at the sa interface. The two stoppers, tile expansion and substrate contraction, and the two adhesive modes remain fully bonded ($A_d = 0$) over the whole computed range. The two drivers debond at similar loads, substrate expansion slightly earlier.

We note in passing that the late flattening of the A_d curves, an apparent strengthening, is an artifact of the static formulation: equilibrium across the interface builds compressive tractions within the remaining bonded region. In practice, inertia governs this stage (Feldfogel & Rabinovitch 2026). This artifact has no influence on which modes debond and which do not.

3.3 The debonding fronts

In terms of the evolution of the debonding fronts, the two drivers debond essentially by one route, see Fig. 6. Lobes nucleate at the four corners, grow inward along the diagonals, and coalesce into a continuous annulus near $A_d = 0.2$. Following crack coalescence, the fronts contract radially toward the center while keeping a circular shape.

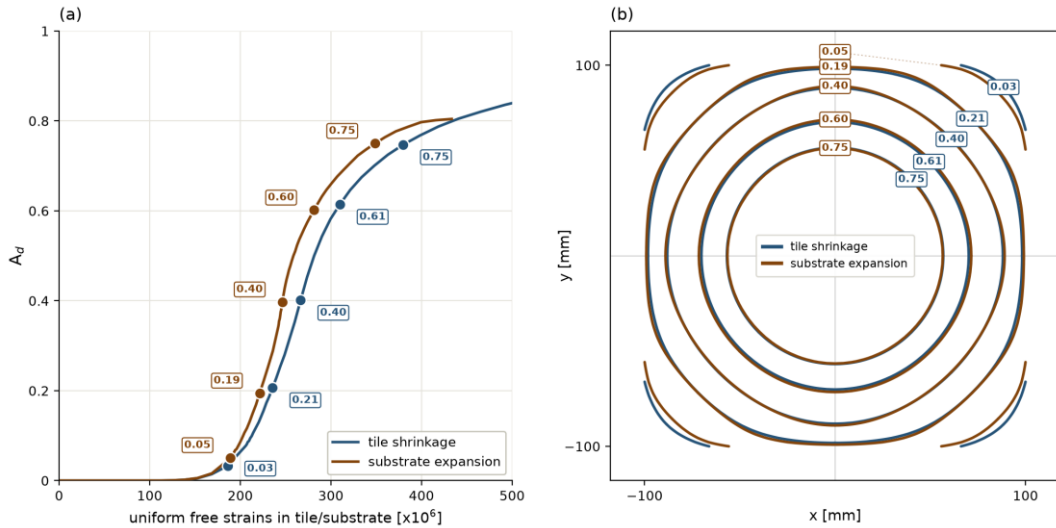


Fig. 6. The two drivers. (a) A_d against the uniform free strain applied to the tile (tile shrinkage) or the substrate (substrate expansion). (b) Debonding fronts at the sa interface at the states marked in (a); in both panels, labels give the A_d of each marked state.

3.4 Why drivers debond and stoppers do not: peeling tractions at the corners

To see why drivers debond and stoppers do not, we examine the peeling tractions at both interfaces for the representative pair of tile shrinkage and tile expansion, Fig. 7. All are taken at the first, pre-debonding load increment and per unit free strain, so that the six modes are compared at equal DFSI magnitude (Table 1). At that stage the response is linear, and superposition applies. The largest gradients and extreme values of the peeling tractions, positive and negative, occur near the corners, see the corner zoom-ins in the right column of Fig. 7. Under tile shrinkage, the largest peeling (tensile) traction occurs at the corner of the sa interface, Fig. 7(b) and Table 1, which is where debonding nucleates, see Fig. 6(b). Under tile expansion, the same corner carries a compressive traction of nearly equal magnitude, Fig. 7(f): the interface is pressed shut. This antisymmetry of drivers and stoppers at the sa corner is what selects the drivers.

Table 1. Peeling tractions T_z under the six basic modes, per unit free strain (unit DFSI magnitude), at the first, pre-debonding load increment ($A_d = 0$): at the free corner of the sa interface, and at the peak of the at interface, with its sign. The at peak lies at the corner in the four driver and stopper modes and about 5 mm inside it, along the diagonal, in the two adhesive modes. Free-strain vectors (s, a, t) and DFSI vectors $[DFSI_{sa}; DFSI_{at}]$; the last column gives the outcome over the full equilibrium path.

basic mode	free strains (s, a, t)	DFSI [$sa; at$]	$T_z(sa)$, corner [10^{-5} kN/mm ²]	$T_z(at)$, peak [10 ⁻⁵ kN/mm ²]	ratio	outcome
tile shrinkage (driver)	(0, 0, -1)	[0; +1]	+2.602	-0.647	4.02	debonds at sa
substrate expansion (driver)	(+1, 0, 0)	[+1; 0]	+2.824	-0.608	4.65	debonds at sa
tile expansion (stopper)	(0, 0, +1)	[0; -1]	-2.632	+0.642	4.10	no debondin g
substrate contraction	(-1, 0, 0)	[-1; 0]	-2.862	+0.603	4.75	no debondin

(stopper)						g
adhesive expansion	(0, +1, 0)	[-1; +1]	-0.226	+0.142	1.59	no debonding
adhesive contraction	(0, -1, 0)	[+1; -1]	+0.226	-0.142	1.59	no debonding

At the at interface, the peeling tractions of the drivers and stoppers, positive and negative, are at least four times smaller than at the sa interface, Fig. 7 and Table 1. This is attributed to the much larger mismatch of axial and flexural rigidities across the sa interface. For the adhesive modes, whose DFSI loads both interfaces, the at peak is closer in magnitude to the sa corner traction (a ratio of about 1.6), but both are an order of magnitude smaller than the corner tractions of the drivers.

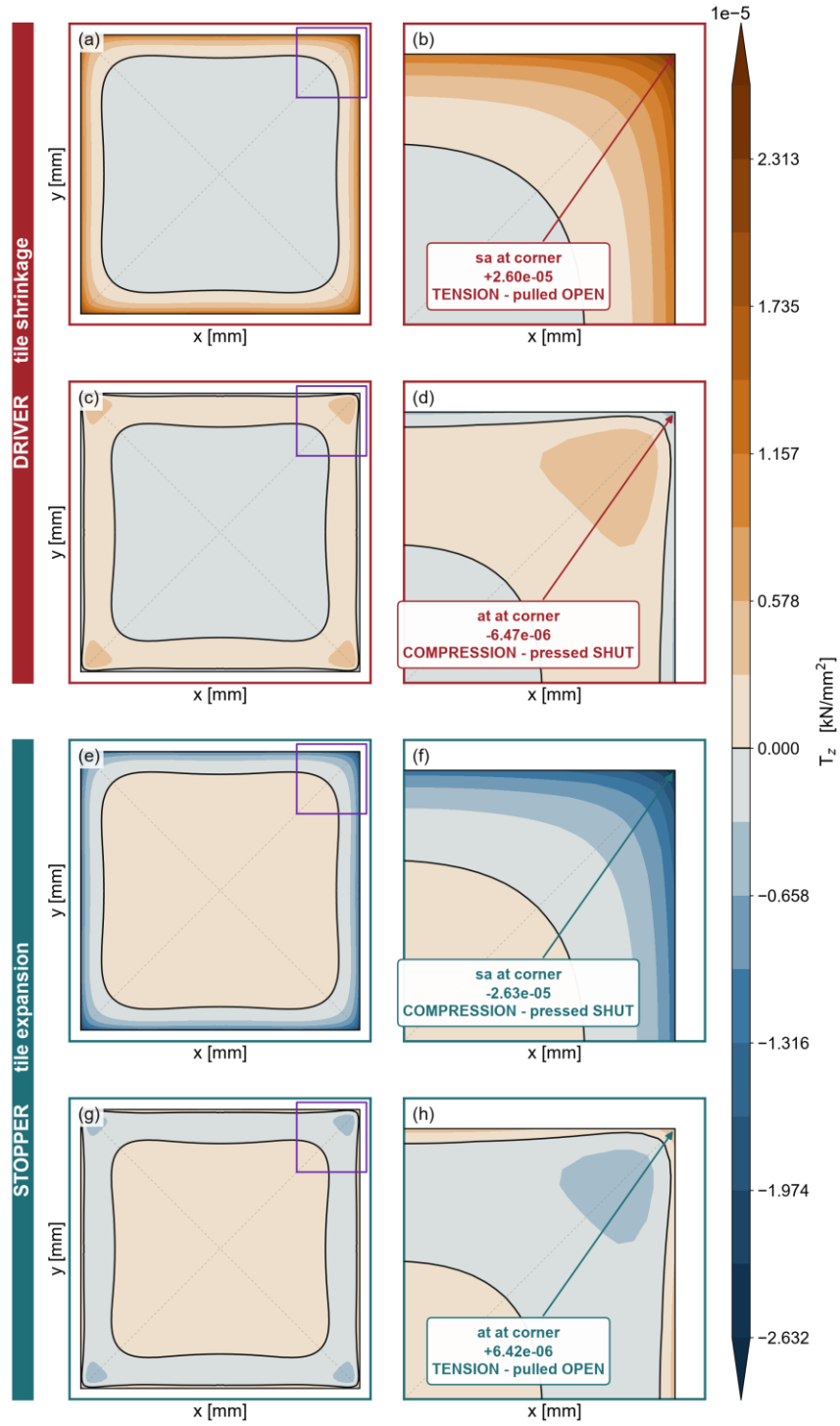


Fig. 7. Peeling tractions T_z at the first, pre-debonding load increment, on one color scale (kN/mm^2 ; positive = peeling): tile shrinkage (driver; a–d) against tile expansion (stopper; e–h), at the sa interface (a, b, e, f) and the at interface (c, d, g, h); left, the entire tile; right, $4\times$ corner zoom-ins. The corner tractions at the sa interface are of nearly equal magnitude and opposite sign.

In posing the hypothesis (Section 2.3), the adhesive modes were read as combinations of a driver and a stopper. Fig. 8 shows that the peeling-traction map of adhesive expansion is well approximated by the combination of tile shrinkage and substrate contraction, supporting that reading. At the sa corner, adhesive expansion leaves a traction of about 9% of that of tile shrinkage per unit free strain (Table 1). This means that, while the driver-stopper model cancellation is not absolute, it does bring the debonding-driving traction to less than a tenth compared to the driving mode. This explains why the adhesive modes did not debond over the whole computed range in the reference configuration, Fig. 5, and why we consider then as neutral compared to the driving modes. This is an engineering ranking demonstrated by computation, not a proof: configurations in which the driver and stopper tractions differ more could create a situation wherein one of the so-called neutral adhesive modes debonds (albeit likely at a much higher load compared to one of the driving modes).

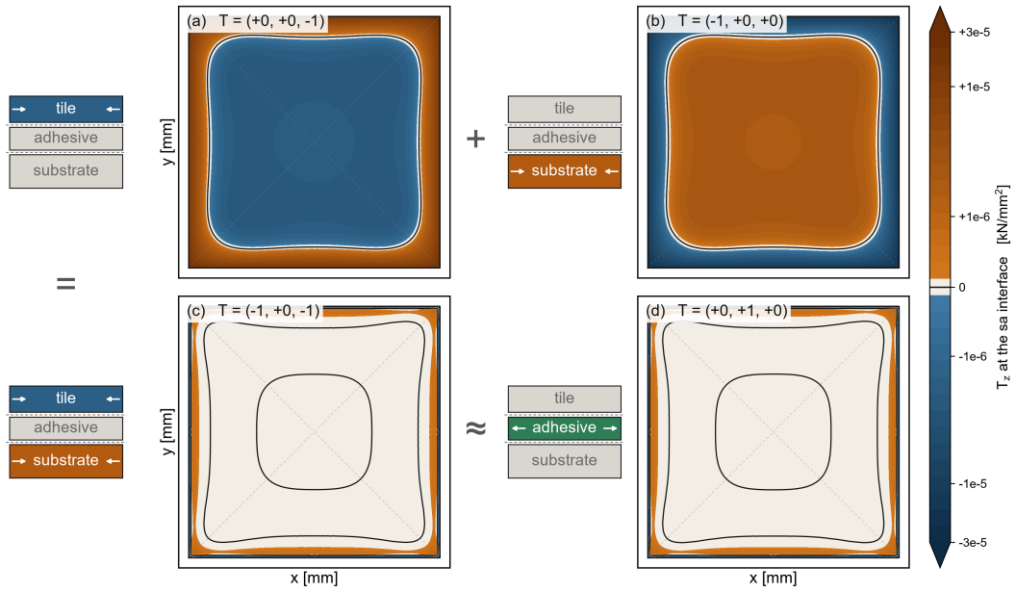


Fig. 8. Adhesive modes as combinations of a driver and a stopper: peeling tractions T_z at the sa interface at the first load increment under (a) tile shrinkage, (b) substrate contraction, (c) their combination, and (d) adhesive expansion; free-strain vectors $T = (s, a, t)$. Panels (c) and (d) nearly coincide.

3.5 Invariance and validity of the corner mechanism across the arrangement

The results so far rest on a single geometry and a single set of material parameters. Does the selection of the drivers, and the corner mechanism behind it, hold more generally? To answer, we tested a full factorial of adhesive modulus (2 and 12 GPa), adhesive thickness

(1.875 and 15 mm), tile modulus (40 and 80 GPa), tile thickness (8 and 12 mm), and substrate modulus (10 and 50 GPa). Each of these $2^5 = 32$ combinations was applied to the 200×200 mm reference tile, a 400×400 mm tile, and a 400×100 mm rectangular tile — tile size and aspect ratio being among the parameters that govern tile debonding (Feldfogel & Rabinovitch 2026) — under the two drivers and the two stoppers: 384 cases in all. The ranges span realistic values encountered in practice. The substrate thickness was held at 200 mm, so that the campaign remains within the rigid-substrate regime of the hypothesis; the reference set lies between the factorial levels and was computed separately. All 384 cases were tested at the same load level: a uniform free strain of $1 \mu\epsilon$ in the loaded layer (the first load increment).

In all 384 cases, the corner traction at the sa interface was peeling under the drivers and compressive under the stoppers, see Table 2 and the left column of Fig. 9: it never changed sign. In all 384 cases it also exceeded, in magnitude, the largest peeling traction anywhere on the at interface, by a factor of at least 2.16, right column of Fig. 9. The at peak, by contrast, takes either sign across the campaign, as it often lies in an interior lobe rather than at the corner, but it is everywhere much smaller, middle column of Fig. 9. The reference set lies well inside the spread of every quantity, as the yellow stars in all three columns of Fig. 9 show. These two features — the sign of the sa corner traction and the dominance of the sa interface — are the ones on which the selection of the drivers rests. Their invariance across the whole campaign shows that the two drivers, and the simple kinematic reasoning that predicts them, hold across a wide range of tiles bonded to flexurally rigid substrates, and not only for the reference set.

Table 2. Summary of the 384-case campaign at the first, pre-debonding load increment ($A_d = 0$). For each of the two drivers and two stoppers (96 cases each: 32 material and thickness combinations $\times$ three tile geometries), the columns give the sign of the peeling traction at the sa corner (number of cases + / –); the number of cases in which the sa corner traction exceeds, in magnitude, the largest peeling traction on the at interface; the number in which the largest sa traction lies at the corner; and the smallest ratio of the two tractions.

basic mode	number of cases	sign of $T_z(\text{sa})$	$T_z(\text{sa}) > T_z(\text{at})$	sa peak at corner	min $T_z(\text{sa})/T_z(\text{at})$
tile shrinkage (driver)	96	96 + / 0 –	96/96	96/96	2.16
substrate expansion (driver)	96	96 + / 0 –	96/96	96/96	2.29
tile expansion	96	0 + / 96 –	96/96	96/96	2.18

(stopper)					
substrate contraction (stopper)	96	0 + / 96 -	96/96	96/96	2.31

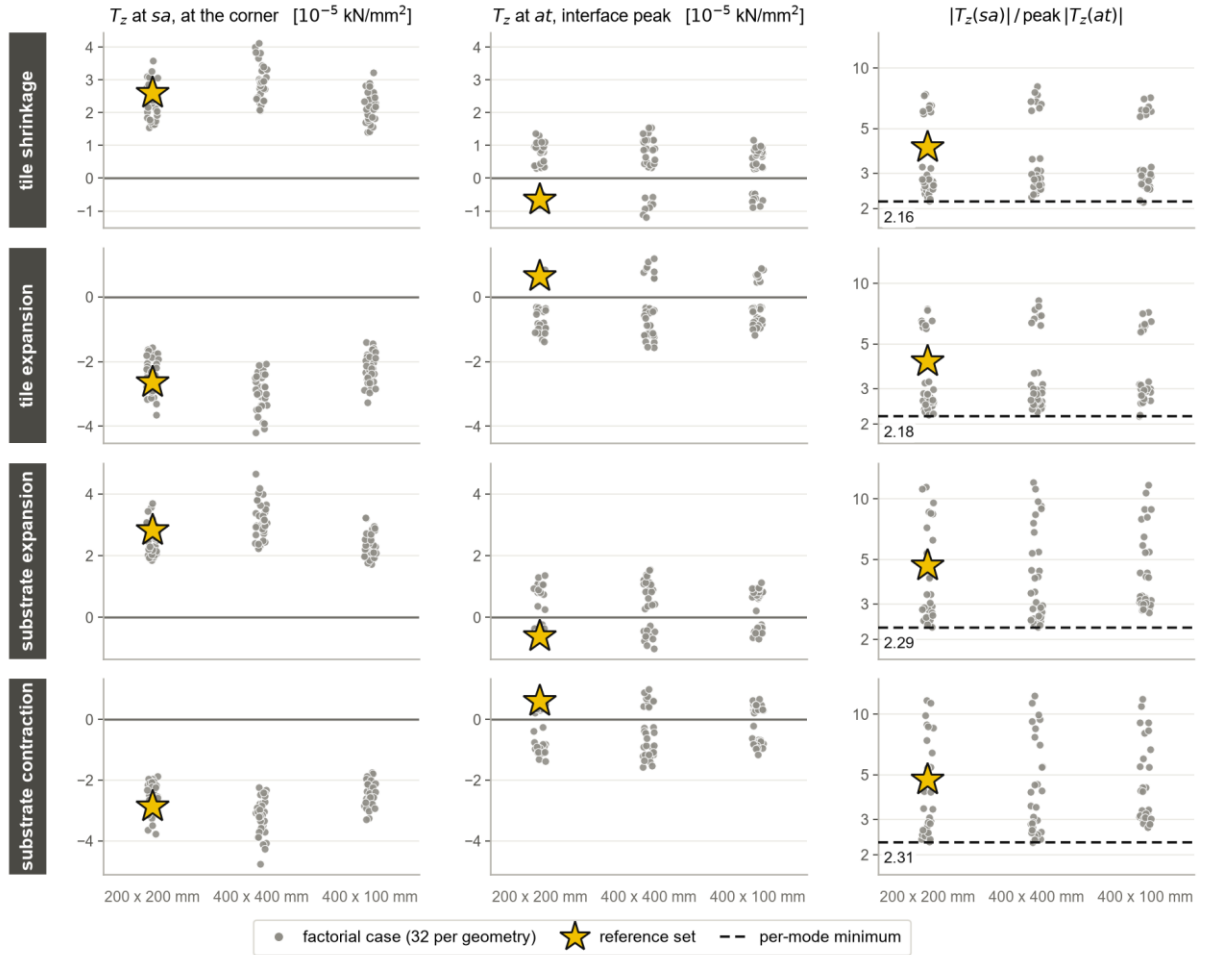


Fig. 9. Invariance of the corner mechanism across the 384-case parameter campaign. Rows: tile shrinkage, tile expansion, substrate expansion, and substrate contraction. Left: peeling traction T_z at the free corner of the sa interface, where its interface peak lies in all 384 cases. Middle: peeling traction T_z at the peak of the at interface, with its sign, on the same axis as the left column. Right: the ratio of their magnitudes on a logarithmic scale, the quantity of Table 2; dashed, the per-mode minimum (2.16, 2.18, 2.29, and 2.31). In every panel, each tile geometry (200×200, 400×400, and 400×100 mm) carries the 32 material combinations of the factorial, spread slightly for visibility; star, the reference set, which lies between the factorial levels. All values at a uniform free strain of $1 \mu\epsilon$ in the loaded layer.

4 Summary and conclusions

This study set out to identify the hygrothermal loads that drive tile debonding, and hence detachment, and to express such loads in a structural-mechanics language. We proposed the differential free strain at the interfaces (DFSI) as that language, used it to order the hygrothermal loading space into six basic modes, and hypothesized, from a kinematic argument at the tile corners, that only two of them drive debonding. We tested the hypothesis with a nonlinear cohesive finite-element model: first on a reference porcelain-on-concrete configuration, through the debonding response, the debonding fronts, and the peeling tractions at the corners; then across a 384-case factorial of layer moduli, thicknesses, tile size, and aspect ratio on flexurally rigid substrates.

The main conclusions and contributions of the study are:

- Two loading modes drive debonding, and hence detachment: tile shrinkage and substrate expansion. Their reverses stop it, and the adhesive modes, each the sum of a driver and a stopper, are essentially neutral. The selection is made at the corners of the substrate–adhesive interface, where drivers and stoppers carry peeling tractions of nearly equal magnitude and opposite sign.
- The selection holds across a 384-case factorial of layer moduli, thicknesses, tile size, and aspect ratio on flexurally rigid substrates: the sign of the governing corner traction never flips, and the substrate–adhesive interface always governs. The engineering common sense from which the drivers were hypothesized is thereby supported over a wide range of practical tilings.
- The differential free strain at the interfaces (DFSI) — at each interface point, the free strain of the lower layer minus that of the upper one, collected into the vector $[\text{DFSI}_{\text{sa}}; \text{DFSI}_{\text{at}}]$ — is proposed as the load parameter of hygrothermal debonding and as a better structural language than heating and cooling: it is dimensionless, maps many hygrothermal states onto one structural response, and prevents misattributing a failure to heating or to cooling. In its terms, the drivers are the modes with a single positive entry, the stoppers those with a single negative entry, and the adhesive modes those whose entries sum to zero.
- The six basic modes bring order into the hygrothermal loading space: under linear, proportional loading of intact interfaces, any uniform loading is their superposition.

- Together, the DFSI and the six modes reduce and non-dimensionalize the hygrothermal loading space, from a continuum of temperature and moisture fields to a few dimensionless coordinates.

The two drivers selected by mechanics coincide with those identified independently in field surveys of detached tiles. For practice, the message is direct: within the assumptions of Section 2.4, it is the loadings that expand the substrate relative to the tile — a rain-swollen substrate, or tiles chilled rapidly over a warm wall, as in a summer hailstorm — that threaten detachment, whereas loadings of the reverse sense do not.

Acknowledgements

Oded Rabinovitch gratefully acknowledges the financial support of the Abel Wolman Chair in Civil Engineering.

This research was funded by the Israeli Ministry of Construction and Housing (order number 4501609646). This financial support of this research is gratefully acknowledged.

Appendix A. Mesh convergence

The reference case (tile shrinkage) was re-solved on meshes of 10, 5, and 2.5 mm, Fig. A1. The A_d -load curves of the three meshes practically coincide, Fig. A1(a). The opening at the sa free corner at the first increment, from which the corner traction follows through the cohesive law, converges monotonically, by +6.3% and then +2.3% per halving of the element size; extrapolation places the remaining error at 2.5 mm at about 1.5%, Fig. A1(b). Its sign never changes, and the ratio of the sa corner traction to the peak at traction stays between 3.97 and 4.65. The mesh used in the paper agrees with the 2.5 mm mesh to within 0.5%.

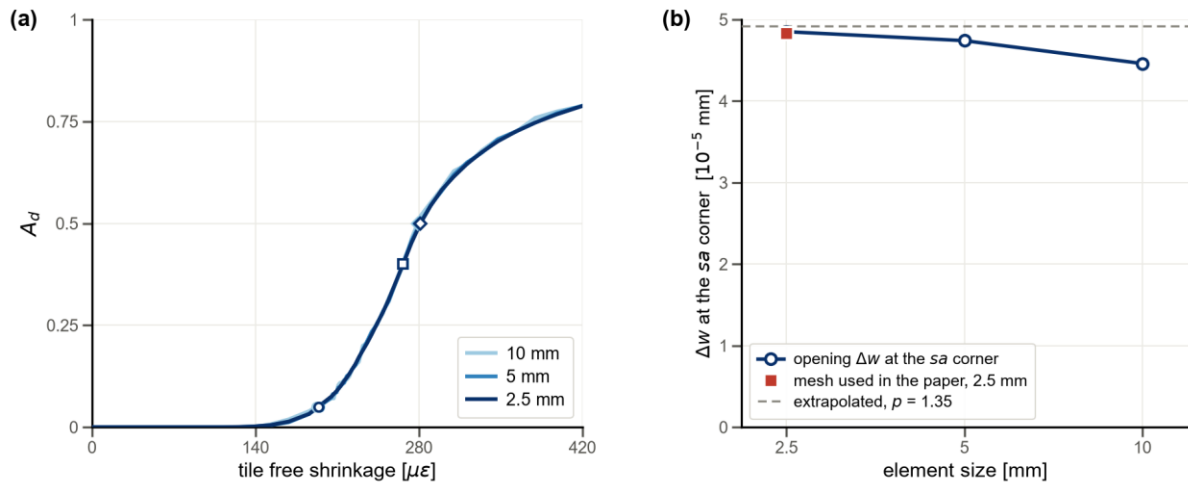


Fig. A1. Mesh convergence under tile shrinkage. (a) A_d against the tile free shrinkage for element sizes of 10, 5, and 2.5 mm. (b) Opening Δw at the sa free corner at the first load increment against element size; square, the mesh used in the paper; dashed, the extrapolated value.

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