THE CRUCIAL NEED FOR COMPUTER MODELLING OF TILING SYSTEMS

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INTRODUCTION

While most ceramic tiling systems perform to expectations, any failure compromises the reputation and growth of the industry. This indirectly has an adverse impact upon all manufacturers, merchants and installers. Although there are several different types of tiling system failures, very few are directly related to unforeseen characteristics of the tile. An exception would be the moisture expansion of a tile, particularly since the accepted accelerated test method may provide a poor indication of the likely in-service long-term behaviour. In the case of some tile bodies, the expansion induced by a 24-hour boil, as used in EN 155 and ISO 10545-10, corresponds to the natural expansion that occurs in about 12 to 24 months after production [1], rather than the estimated value of 36 months that had previously been assumed [2]. Since the kinetics of natural moisture expansion can generally be expressed in terms of a logarithmic function, the accelerated 24-hour boil may significantly underestimate the total amount of expansion that occurs over a long period of time. However, much of this expansion may occur prior to the tile being installed.

Although moisture expansion of the tile will contribute to differential movement failures, other factors are normally involved and are often far more significant [2, 3]. These include concrete drying shrinkage, poor tile fixing practices and the use of unsuitable fixatives. The system must also be able to tolerate the additional stresses that result from the reversible thermal and moisture movements that will occur as the system is exposed to varying atmospheric conditions and usage situations.

Most other types of failures are due to either using first quality products in inappropriate situations (poor specification of the tiling system), or to improper installation practices (failure to follow the specification). Widespread adequate specification of tiling systems is a complex matter that has been partly addressed by the development of the existing (and pending) product and installation Standards. It is also being addressed by the introduction of computer-based expert systems [4] as previously advocated [5]. However, there is still the fundamental underlying requirement for comprehensive engineering data to determine appropriate compliance limits and to permit the development of engineering design codes that can support the project decision-making process. While there is an obvious need for such information, it is expensive to obtain, and there is no implicit requirement for any individual party to provide it.

Computer modelling of tiling systems offers a cost-effective means of determining the strains and stresses that may develop when the system is subjected to specific loading conditions. In some circumstances, partial analytical models of tiling systems may provide sufficient understanding, and at a low cost. In addition, empirical relationships have also been developed from experimental studies, for example the prediction of impact damage due to rolling wheel loads [6-9]. The advantage of any relationship that is expressed in mathematical terms is that one can readily determine the influence of a specific variable.

This paper reviews some of the published studies that relate to differential movements within tiling systems. It broadly considers some of the aspects that have limited the more widespread use of modelling techniques for developing engineered solutions for specific scenarios. It is important to recognise that while some simple theoretical models are adequate for specific purposes, others can be misleading. There is thus a compelling need for experimental verification, although this may be hard to obtain for a number of reasons. For instance, one may obtain very different results from experiments conducted under conditions of constant temperature and relative humidity, compared to the variable conditions experienced on site. Thus, one must exercise care in applying laboratory-generated results to practical situations.

There are a number of different strategic approaches that can be taken in such work. These include using a macroscopic perspective or more detailed analysis, and evaluation of the stresses that are generated along or across the tiling system. Such work should consider the effects of structural movements, including any pre-existing stresses within the substrate. One must particularly consider the time-dependent nature of adhesive setting reactions and differential movements. Ultimately, most approaches are acceptable and useful, as each tends to supply a partial solution to the overall problem.

MOVEMENTS CAUSING STRESSES IN TILING SYSTEMS

The Building Research Establishment has published data on the estimation of thermal and moisture movements and stresses in Digests 227 to 229 [10-12]. Recognition of the location and extent of movements in building materials and components is essential for the satisfactory design of joints and fixings and the prevention of cracking [10]. The presence of restraint offered to potential movements will determine whether differential movement occurs or whether stresses result. In most cases both effects will be present, with partial restraint limiting the actual amount of movement and giving rise to a "balancing" stress. It has been suggested [10] that sophisticated methods are little better than elementary ones for estimating the resultant stresses, because of the difficulty of accurately predicting restraint and the other variabilities in materials and conditions that occur in practical building situations. Thus, the essential needs are to recognise where inherent deviations are liable to occur and to determine the order of magnitude of their effects, so that adequate provision can be made for them in design. The Digests discuss movements, their sources and design strategies for accommodating them, and the causes of deformation and stress [10]; analyses thermal and moisture effects, and includes tabulated data to assess the change of size and shape of materials [11]; and gives guidance on estimating deformations and associated forces and stresses given various stated assumptions [12]. While the Digests only cover thermal and moisture effects, they note that other types of movement also need to be considered, the most widely relevant being structural deflections, creep (especially creep-shortening of columns) and foundation movements. Also, they do not deal with the practical consequences of movements in particular parts of buildings.

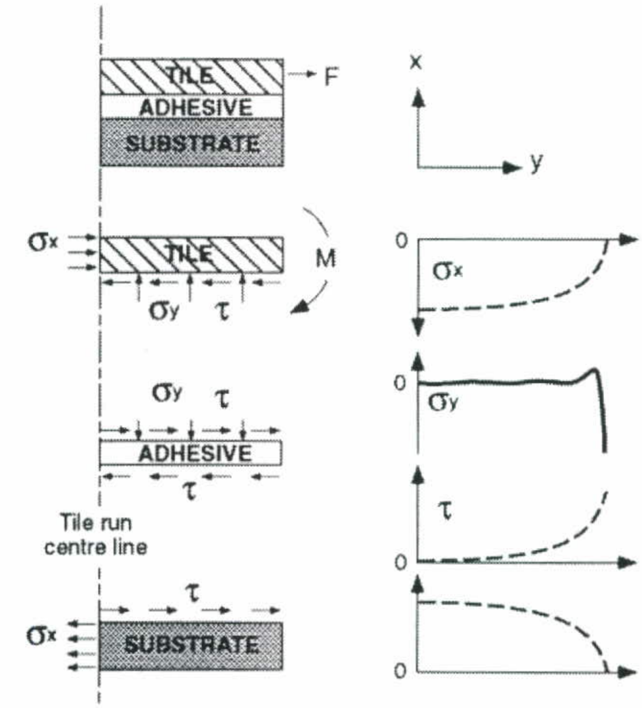


Fig. 1. Stress distributions in planar tiling system from differential shear analysis (--) and concentrated shear analysis (-).

PARTIAL ANALYSES OF TILING SYSTEM STRESSES

Banks and Bowman [13] presented a brief review of some of the published analyses for determining the stresses within tiling systems. These vary widely in the approaches taken and as they are quite dependent on the assumptions made, each method has its limitations. Vaughan *et al.* [14] analysed the tensile and compressive stresses induced by differential movement causing bending of an unrestrained layered system (as subsequently used by Harrison and Dinsdale [15]) assuming that the thickness of the system is small compared with its lateral extent, and that displacements arising from the induced curvature are small compared with the thickness. The analysis does not include any derivation of the shear and peel stresses in an adhesive layer.

Toakley and Waters [16] considered a tile run adhered to a thick solid substrate, either fully restrained laterally or unrestrained laterally, as a "bonded plate" subject to buckling due to compression following tile expansion. They referred to prior work showing that "the stresses required to produce buckling in the bonded plate were considerably greater than the compressive strength of the tiles" when "the significant effects of eccentricity of loading are neglected". They determined the relation between the in-plane compression forces in the tiling due to tile expansion, the initial out-of-planeness of the tiling, and the tensile (peel) stresses tending to cause adhesion failure. Adhesive shear stresses were discussed but not estimated.

Bernett [17] determined the compressive stress induced in a tile run by tile expansion, considering drying shrinkage, elastic deformation and creep of the grout, and elastic deformation of the tile. He estimated adhesive shear stress by assuming that this was confined to the last tile in the run. Bowman [9] extended this study, considering also the shrinkage of the substrate and compression of the movement joint; while the derivation of adhesive shear stress requires revision, attention was given to the consequences of low levels of adhesive coverage.

If the in-plane deformation of tiling and substrate is neglected, the shear stress in the adhesive layer is constant and may be deduced simply. This is an unrealistic assumption, and adhesive shear stress varies, being greatest at the ends of a tile run (at movement joints, if functioning) [13]. A first approximation in estimating this variation is to consider that the tiling and substrate remain planar and deform in tension or compression only, and that the adhesive deforms in shear only, with no stress variation normal to the plane of the tiling. This "differential shear" approximation was applied many years ago to the lap joint between adherends [18], and recently to the tiling system (J. Blanchard, Ove Arup & Partners, London, 1993, personal communication). The forces induced by differential movement in tiles and substrate are not co-planar, so that moments are exerted on the tiling, causing tensile (peel) and compressive stresses across the adhesive layer, as shown in Figure 1. A result from the differential shear analysis (DSA) for the tiling system can be used to provide an estimate of this peel and compressive stress distribution, assuming that the shear stress is highly concentrated at the ends of a tile run (J. Blanchard *ibid.*). Banks and Bowman [13] have referred to this estimation of peel and compressive stresses as the "concentrated shear" analysis (CSA) for the tiling system.

Wagneur [19] has warned of the dangers of the trend to fix wall tiles on increasingly young substrates in the general context of the causes of debonding. He not only considered the effect of thermal movements and reversible and irreversible moisture movements, but also the creep of the substrate. He provided a simple schematic representation of stresses and deformations of a tiling system where the substrate shrinks. He assumed that any size change in the tiles was constant throughout their thickness, and that the fixative only took up shear forces. This results in the tile layer being put into compression. If the tiling remains bonded, the greatest deformation of the fixative layer will occur in the vicinity of the tiling borders, where the maximum shear stresses will occur. The latter stresses are all higher when the adhesive is more rigid. There will be no compressive stress in the tile layer at the point where the maximum shear stresses occur, but the compressive stress will increase further away from the perimeter as it substitutes for the adhesive shear stresses. Wagneur also showed how the presence of compressive stresses in the tile layer and shear stresses in the adhesive layer give rise to a bending moment. Many of the above relationships are clarified in simple diagrams that generally agree with the more complex figures given in this paper. The latter, having been derived from finite element analysis, are influenced by the presence of grout joints. Wagneur used Hooke's Law to estimate the compressive stress in the tiling, assuming that the substrate deforms to the same extent as the fixative. Wagneur also provided a simplified relationship to calculate the maximum shear stresses in the adhesive plane.

Wagneur explained the debonding phenomenon in terms of progressive failure, where it is initiated at locations where the maximum shear stresses occur (free edges, flexible joints, outgoing corners, a crack or movement joint in the substrate). Once debonding is initiated at one of these locations, the segment in which the shear stresses are concentrated displaces to the immediately adjacent zone, explaining how the tiling could gradually debond. Where localised bulging occurs away from the tiling edges and discontinuities, failure will have occurred due to tensile stresses. In such situations, the rows of adhered tiles not only constitute abutments for the debonded zone, but also become more subject to shear, although they are partially restrained by being bonded (by grout) to the run of adjacent tiles, some of which are still bonded and thus effectively restrained. Wagneur indicated that if the grout is strong, it has a crushing resistance very close to that of the tiles, and that the joints absorb no deformation and undergo compressive stresses similar to those of the tiles, shear stresses being transferred to the periphery of the tiling. Where the grout is more compressible, it is more likely to absorb movement, while also subjecting the tile edges to some shear stress, albeit less than at the perimeter of the tiling.

FINITE ELEMENT ANALYSES

For the lap joint, closed-form analyses have been developed that reduce the approximations in the differential shear analysis. However, the applications of these analyses "are limited because only the simplest geometries and boundary conditions can be accommodated. For more complex situations, approximate numerical solutions become necessary" [20]. Finite element analysis (FEA) divides the system into small elements, and is suitable for adhered systems because elements with different material properties can be interfaced. FEA is available in commercial packages, and is widely applied to the stress analysis of adhesive/adherend systems [20, 21]. The application of FEA to tiling systems has been reported briefly by Van Den Berg [22] and Goto *et al.* [23].

In its simplest form, FEA is applied assuming linear-elastic material properties. For these properties, some peak stresses occur at adherend edges and are theoretically infinite ("singular") [20], so increase as FEA grid size is reduced, approaching infinity for zero grid size. "In several analyses these sharp peaks were reduced to the level of the experimentally measured ultimate stress by assuming elasto-plastic or visco-plastic behaviour of the adhesive material" [24]. Practical experience has shown that adhesives in tiling systems creep to relieve peak stresses [16, 17].

Standard test methods for adhesives yield average failure stresses over the adhered surface, which are not suited for comparison with theoretically obtained peak stresses to predict failure. The actual loading causing failure of a tiling system, with singular or non-singular peak stresses, can be determined from the measured failure loading of a similar physical experimental model, and the FEA peak stresses in system and model (computed with the same FEA grid size) [20]. Thus, linear-elastic FEA can be used to show the influence of changes in system parameters on maximum stresses, and thus propensity to failure, if the same FEA grid size is used in the cases compared, as shown in Appendix 1.

Naniwa *et al.* [25] used FEA to study the internal stress distribution caused by differential movements of exterior wall tiling systems due to the effects of two conditions: cold to hot, and wet to dry repetitive cycles. They also studied the effect of the characteristics of the system components on the stresses produced at the interfaces between them, while noting that further studies should be undertaken on the effect of stress relaxation due to creep.

Their model consisted of a two-dimensional cross-section of a wall using the half width (30 mm) of a 9 mm thick tile and a 4 mm wide grout joint. The tiles were applied to a 150 mm thick concrete wall with either normal mortar or combinations of normal and lightweight mortars.

They concluded that under both sets of conditions there were two locations where delamination would tend to occur due to the in-plane shear stress: at the interface between the tile and the bonding mortar at the tile edge, and behind the tile edge at the interface between the concrete and the substrate mortar. Under cold to hot conditions, the maximum transverse stresses also occurred at the same locations. However, under wet to dry conditions, there were also significant in-plane tensile stresses at the centre of the tiles at all interfaces. Under cold to hot conditions, it was found that the stress could be reduced by decreasing the elastic modulus of the mortar (increasing its deformability), especially at the interface between the concrete and the substrate mortar. Under wet to dry conditions, when the drying shrinkage of both the bonding and substrate (lightweight) mortars were high, the stress increased at the interface between the substrate mortar and the concrete. Thus, repetitive drying cycles (after the infiltration of rainwater) would create extreme stresses that could result in debonding.

The use of lightweight mortar reduced the thermally induced stresses but not the moisture-induced stresses. The physical characteristics of the ideal mortar were found to be low elastic modulus, low mass density, low thermal expansion coefficient, low thermal conductivity and high specific heat.

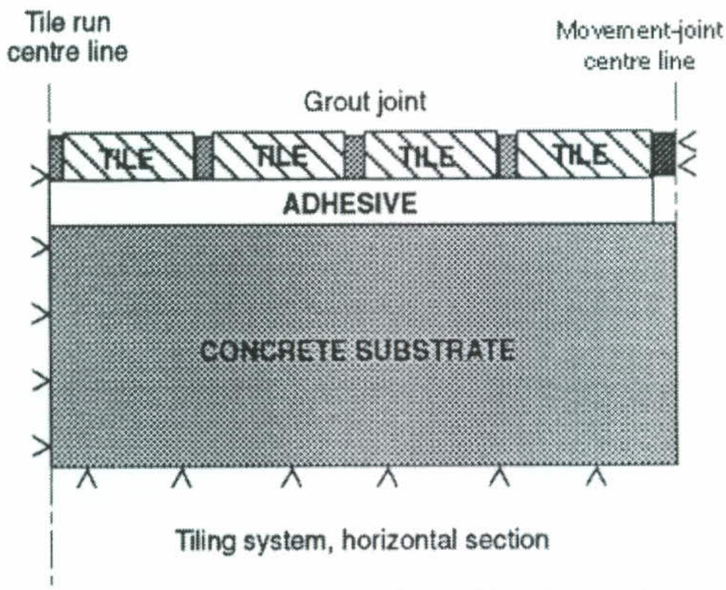


Fig. 2. Finite element analytical model for a horizontal section of a tiling system.

McLaren *et al.* [26] used FEA to study the behaviour of different materials in floor tiling systems subject to bending and deflection. Modelling of several hundred variations of three common framing systems was performed to identify the effects of floor thickness and stiffness, continuity, location of expansion joints, tile size and span length. These parameters were modulated for five permutations of adhesives and grouts, since there was particular interest in the potential benefits of recently developed polymeric materials.

They used a finite element model of the composite action of three beams (tile layer, adhesive bed and substrate) restrained by horizontal shear forces at their interfaces under a load causing deflection of a simply supported floor system. Each model was loaded to theoretical failure, defined as occurring when a stress for any component exceeded its predefined failure level.

Their initial findings included the fact that there was a significant correlation between the shear stress in the tiles and the stiffness of the grout. The shear stress distribution across the tiles was concentrated at the edges of the tiles at the grout joints. Increasing the elastic modulus of the grout reduced this stress. They were thus able to deduce that the installation

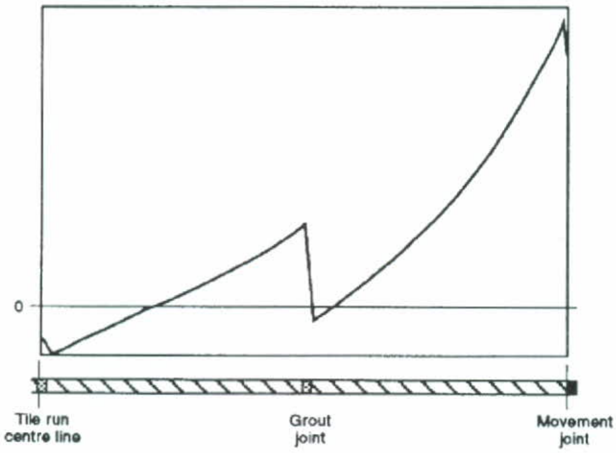


Fig. 3 Adhesive shear stress at tile surface for uniform tile expansion.

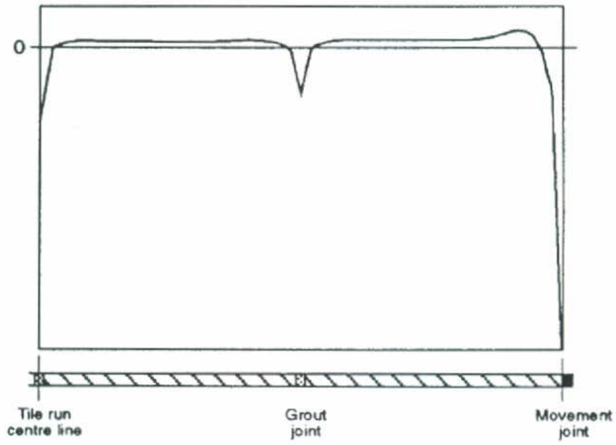


Fig. 4 Adhesive peel stress at substrate surface for uniform tile expansion

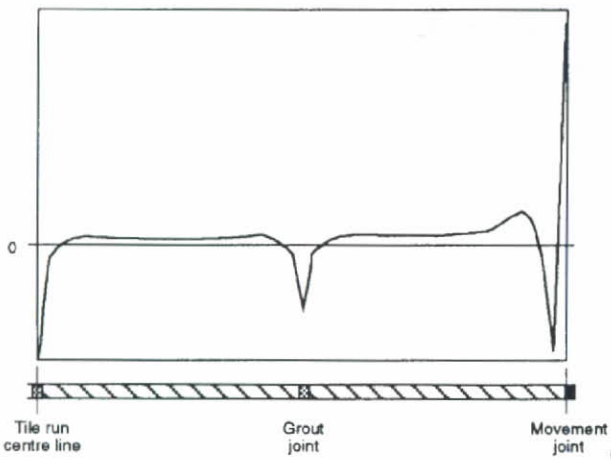


Fig. 5 Adhesive peel stress at tile surface for uniform tile expansion

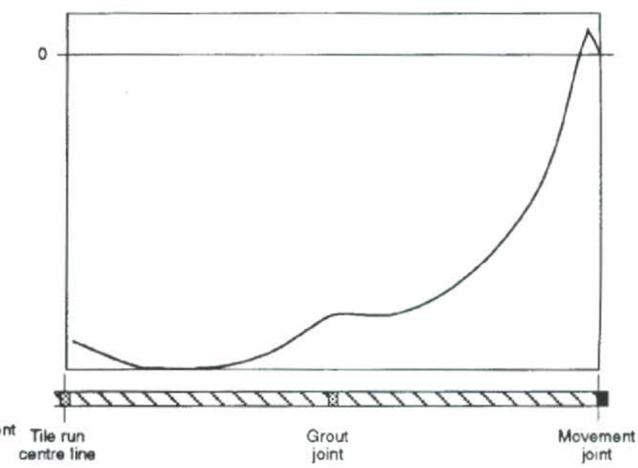
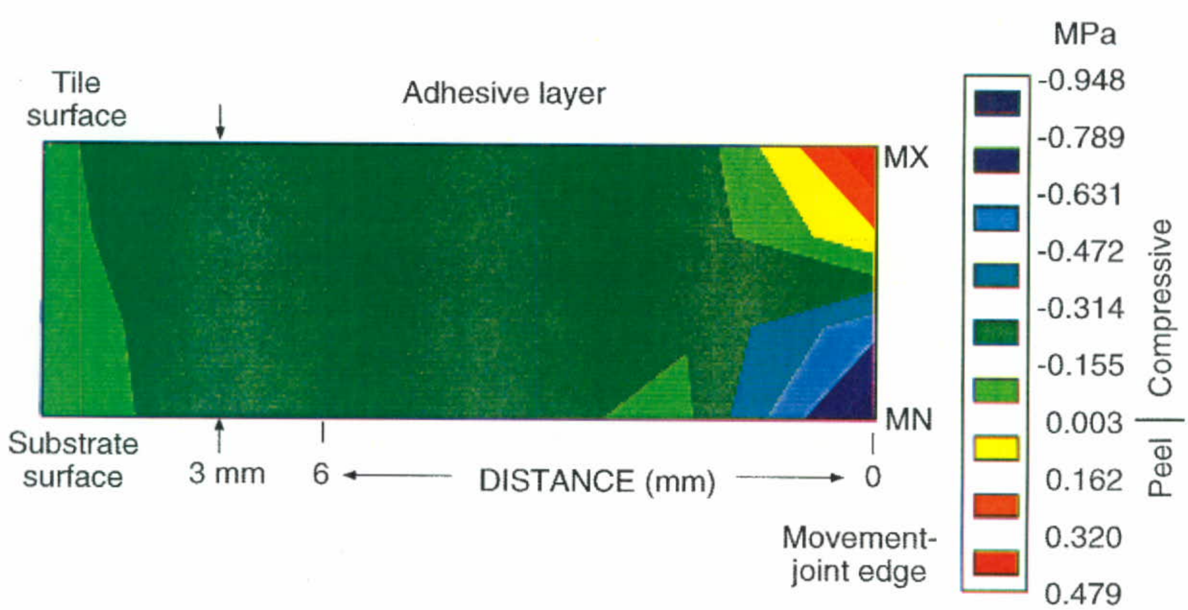


Fig. 6 Tile surface tensile stress for uniform tile expansion

of expansion joints in the middle third of aspan over a simply supported substrate would only contribute to the failure of the tile configuration. From their analysis, the allowable deflection increased if an expansion joint was positioned at each support.

They also found that as the properties of the elements changed so did the stress distribution: smaller tiles (plan dimension) seemed to generate larger stresses with respect to less deflection; thicker tiles and thicker mortar beds decreased stresses; and a more uniform modulus of elasticity between elements decreased the stress slightly. The stress concentrations that led to failure were due to the homogeneity of the composite system: the more dissimilar the elements, the greater the concentration of stresses. This explains why the smaller tile sizes with more discontinuities failed at a lower deflection.

For simple spans, the mode of tiling system failure was generally an initial compressive failure of the grout leading to debonding of the tiles through shear failure of the adhesive. For continuous structures, the tensile weakness of the grout was usually the incipient failure, again followed by debonding. This is consistent with the inability of unmodified cement-



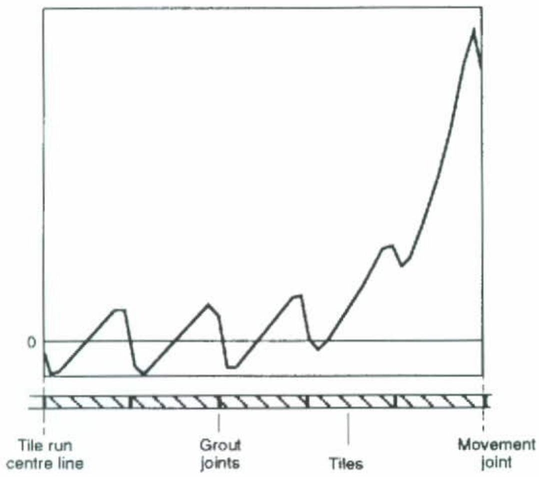


Fig. 8 Adhesive shear stress at tile surface for non-uniform tile expansion.

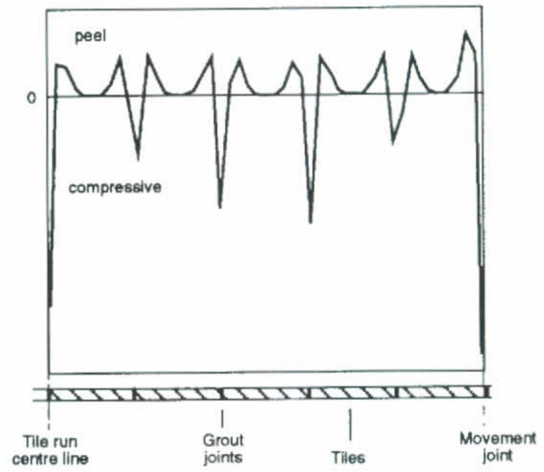


Fig. 9 Adhesive normal stress at tile surface for non-uniform tile expansion.

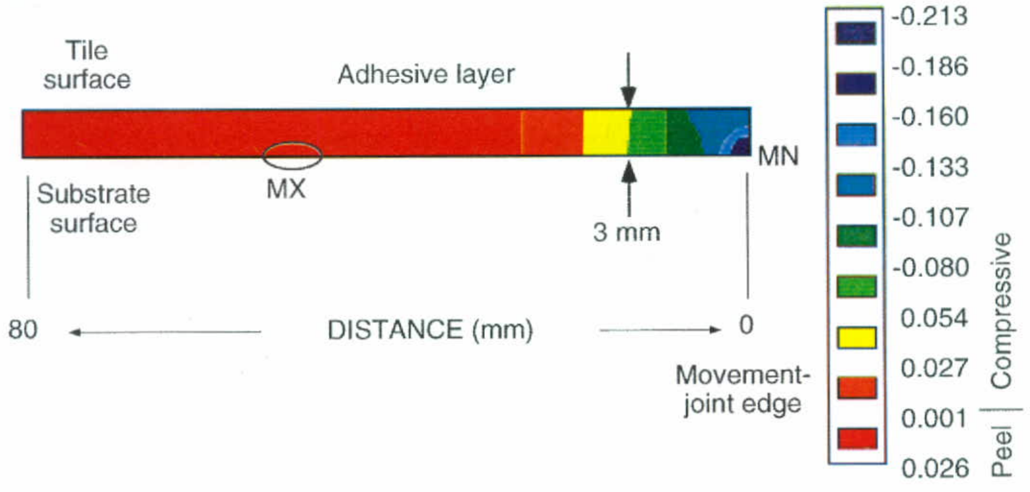
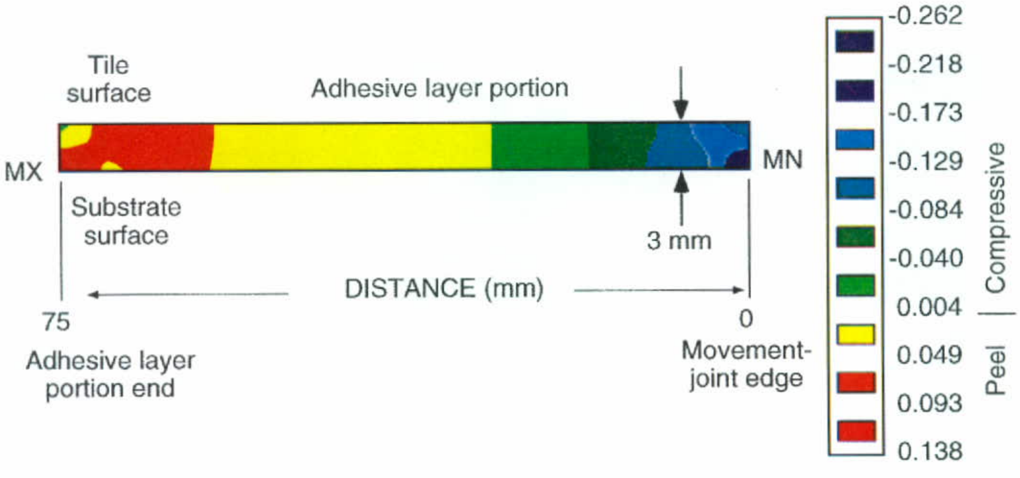


Fig. 10 Normal stress contour plot in adhesive layer adjacent to movement joint for non-uniform tile expansion, with the adhesive having a moderate elestic modulus (25 MPa)



tile expansion, with 50% the adhesive coverage concentrated at the tile ends, and the adhesive having a moderate elestic modulus (25 MPa) based mortars to achieve acceptable results on flexible substrates, where the grout failure occurs due to the stress concentrations that build up between the tiles. However, a notable exception to this trend occurs with ceramic mosaic tiles that exhibit initial failure within the mortar layer. The thinner adhesive layer and the smaller tile size would possibly reduce the ability of stresses to distribute throughout the floor structure.

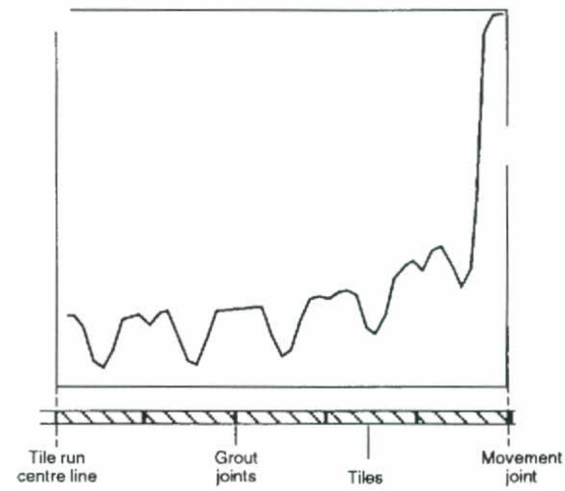


Fig. 12 Tile surface tensile stress for non-uniform tile expansion, with 50% adhesive coverage concentrated at the tile centres

This work suggested that where tiles were polymerically bonded, the design limitations for deflection of simple span structures could be relaxed since failure would not occur until deflections occurred in excess of the practical limitations of the structure. Thus the design would be covered by the structural code and the strength of the concrete. However, for continuous substrate systems, where failure is likely to be initiated by tensile failure of the grout, the relaxation of the deflection limitations is more dependent on providing proof of the strength values of materials.

Laboratory tests were conducted on 6700 x 1220 x 200 mm reinforced concrete slabs tiled with 200 x 200 x 9.5 mm porcelain tiles, with two-point loading over a 6.1 m span. The slabs were incrementally loaded until failure. Between the load increments, the slabs were inspected for indications such as grout failure, tile debonding and slab cracking. This provided valuable insight into the succession of events that lead to tile failure and confirmed the FEA results. In addition to the load tests, material tests were also conducted on the tile, adhesive, grout and concrete in order to determine their compressive and shear strengths.

The laboratory data enabled refinement of the finite element model, including true modelling of a reinforced concrete slab. To verify the model, it was adapted to simulate one of the laboratory tests, where a non-linear analysis was approximated by loading the system incrementally. Where the model output indicated that a grout joint had failed, a tile had debonded, or a tensile crack had developed in the concrete, the model was changed accordingly (by virtually eliminating the failed element) and the next increment was applied. The curves predicted by FEA for the upper and lower bound of concrete strength correlated well with the laboratory test results; they were especially accurate when representing practical service load conditions.

The development of the refined mathematical model has enabled the simulation of a myriad of different installation situations without the cost and time associated with full-scale testing. The finite element modelling has shown that the behaviour of ceramic tile installations using advanced latex and epoxy compounds differs significantly from traditional cement-based mortars and adhesives, and that the design rules for the traditional fixatives should not be applied to the polymeric materials. This work resulted in modifications being suggested to the relevant installation procedure. It also suggested several other areas which require further study.

Banks and Bowman [13] considered a representative floor tiling system subject to tile moisture expansion and substrate drying shrinkage, and compared the results obtained by FEA with those obtained by DSA and CSA. The stress distributions predicted by these partial analyses are shown in Figure 1. It should be noted that differential movement causes the force F, which is restrained by shear on the base of the tile, resulting in the moment M. This moment causes the end of the tile to "dig in", resulting in peel and compressive stresses in the adhesive

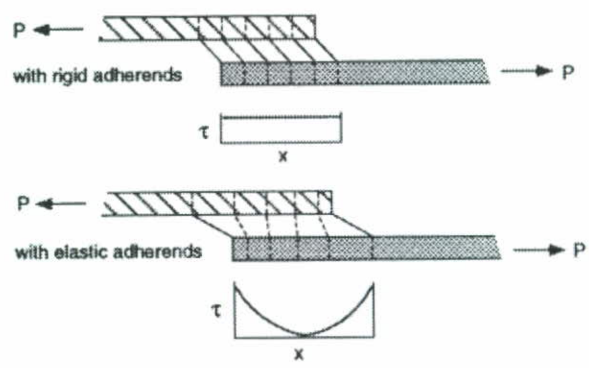


Fig. 13 Exaggerated deformations in a loaded single lap joint, and resultant shear stress.

Complete adhesive coverage was assumed, the tile run was considered to be restrained laterally at the centre-line of a movement joint and the substrate was unrestrained (Figure 2). The 100 mm thick concrete was modelled as a 8 mm thick substrate, but with 12.5 times the elastic modulus, due to a limit on the total number of finite elements. Although tile expansion and concrete shrinkage proceed with time, and creep also occurs, the effects of any time variation of system stresses and strains were purposely neglected. Figures 3-6 respectively show the adhesive shear stress at the tile surface, the adhesive peel stress at the substrate surface, the adhesive peel stress at the tile surface, and the tile surface tensile stress. The latter has important implications for the positioning of strain gauges where they are used to monitor the development of stresses in the underlying adhesive bed. Since the stress is tensile rather than compressive, it could cause crazing of the glaze if excessive. Figure 7 gives the peel stress contour plot in the adhesive layer adjacent to the movement joint.

Figures 1 and 3-5 allow a comparison of the general shape of the curves obtained by the different analytical methods. FEA enables the effect of the grout joints to be determined. For the representative system studied, the DSA results for adhesive shear stress and grout compressive stress were 80-85% of the FEA results. Hence, in such systems, these stresses might be inferred from DSA results. The effect on adhesive peel and compressive stresses of changes in system parameters could not be inferred from CSA results. Corrections to Table 2 Banks and Bowman [13] are given in Appendix 2 to this paper.

It was found that halving the adhesive layer thickness significantly increased the adhesive shear stress while reducing the adhesive peel stress, and little changing the other stresses (except for a large increase in grout compressive stress for the low modulus adhesive). Reducing the elastic modulus of the adhesive by a factor of 20 reduced all stresses by factors of about 3 to 7. However, Divisional test results had shown that the failure shear stress of the low modulus adhesive was about a tenth of that of the moderate modulus adhesive. In such cases, the low modulus adhesive would appear more likely to fail. The partial analyses indicated that the adhesive shear, peel and compressive stresses, and the grout compressive stress all increased appreciably for the low modulus adhesive when the movement joint spacing was increased by a factor of 4.

The authors have also concluded from mainly unpublished associated computations for this case (including those for the appended corrections), that while FEA provides a general solution, the shear, compressive and peel stresses obtained for the adhesive depended on the finite element grid size. Thus, the prediction of failure in a tiling system requires the testing to failure of a similar physical experimental model, as well as FEA of both the system and the model.

Bowman and Banks [27] considered a representative external wall tiling system subject to thermally induced non-uniform differential movement (from tile transient heating), with full and partial adhesive coverage, using similar constraints to those in Figure 2 and similar assumptions to those in Ref. [13].

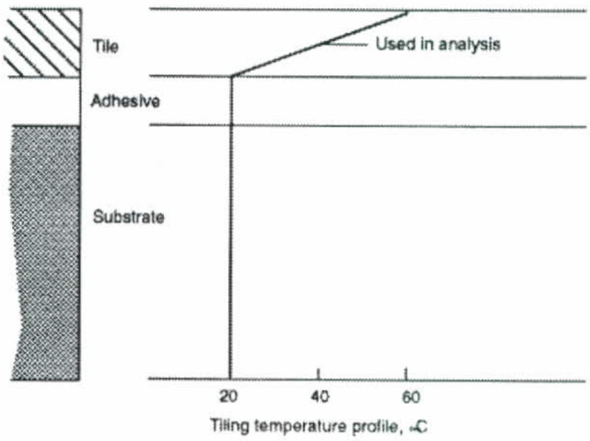


Fig. 14 Temperature profile in tiling system.

Figures 8 and 9 depict the adhesive shear and normal stresses at the tile surface. Figure 10 gives the normal stress contour plot in the adhesive layer adjacent to the movement joint. Figure 11 gives a similar plot where there is only 50% adhesive coverage concentrated at the tile ends. It can be seen that the reduced coverage significantly increases the stress levels. Furthermore, the location of the maxima and minima differ from that induced by uniform differential movement (Figure 7). The consequence of partial adhesive coverage also results in a different tensile stress distribution at the tile surface. Unlike the case for uniform tile expansion (Figure 6), the stresses in Figure 12 are compressive. This is due to the tile surface expanding more than the rest of the tile due to the assumed temperature profile through the tile.

Doubling the adhesive layer thickness significantly reduced the shear and compressive adhesive stresses at both the tile and substrate surfaces. The peel stresses decreased slightly, unlike the case for uniform tile expansion where the peel stresses increased significantly. Reducing the elastic modulus of the adhesive by a factor of 20 reduced the adhesive stresses by a factor of about 5. It also reduced the grout compressive stress by 20%, while decreasing the compression in the surface of the tile towards tension values.

The reduction of the adhesive coverage to 50% significantly increased adhesive shear and peel stresses, the increases being greatest when the partial coverage was at the ends of each tile. The authors have concluded, from unpublished associated computations for this case, that while FEA provides a general solution, the compressive stresses obtained for the adhesive depended on the finite element grid size (but not the shear and peel stresses).

Summary of past FEA studies

The above examples of finite element modelling reveal quite different approaches. It can be seen that the trends that are evident in one loading condition may be quite different in another practical situation. Furthermore, in most practical situations, there will be several different types of movements occurring simultaneously. Tiling systems are very complex, and it must be noted that the past studies have made several simplifying assumptions. These include an assumption that the substrate is stress-free at the time of tiling, and that it is planar and has uniform thermal and moisture movements. The adhesive is assumed to have elastic rather than viscoelastic properties, and the assumed uniform characteristics are those that are determined under laboratory conditions at one point in time. Adhesive shrinkage is generally assumed to be negligible. The ceramic tile is assumed to be a stress-free rectangular prism with planar surfaces and two pairs of parallel edges. It is assumed that the grout joints are free of all adhesive. Movements due to structural deflections, creep, foundation movements and wind loading have generally been neglected.

McLaren *et al.* [26] noted that there are great variations in the published mechanical properties and ultimate stresses of tiles, adhesives and grouts, as is evident elsewhere [11, 19]. Even where the properties are determined for specific materials, one should recognise that laboratory preparation and loading conditions are quite different to those that occur in practice, and there may be a difference in performance.

ADHESIVE EVALUATION FOR TILING SYSTEMS

Adhesive loading in tiling systems

In tiling systems, differential movement between tiles and substrate may be caused by irreversible movement of tiles or substrate, transient heating, wetting or structurally induced bending of the system. Different patterns of shear and tensile (peel) stresses are induced in the adhesive layer, each resulting in adhesive deformation and possibly failure. Failure prediction requires prediction of maximum stresses or strains, and knowledge of failure values.

Adhesive testing

There are standard tests for the shear and tensile strengths of adhesives, which produce differential movement loading by force. Neither test produces pure shear or tensile strain, and the resulting stresses are not uniform over the specimen, though these effects are small for the tensile test. Figure 13 is a classic diagram for the deformations and shear stresses occurring in a lap joint on shear loading. Average values of failure stresses over a specimen are obtained, which are not comparable with the peak shear values resulting in failure in shear tests or tiling systems.

These tests are useful for the comparison of adhesives. This comparison is under ideal conditions and with small specimens. A resulting ranking of adhesives depends on the ambient and other conditions used.

It should be noted that the draft European Norms for ceramic tiling adhesives do not require the determination of the shear strength of cementitious adhesives, or the tensile strength of dispersion adhesives. The logic for this is hard to determine given some of the conclusions that can be drawn from the modelling of tiling systems. It seems evident that the primary cause for tiling system failures is related to both shear and tensile strength. In practical situations, failures probably occur when strain rates exceed creep relief rates [17].

Prediction of stress and strain in tiling systems

Shear deformation method

Some adhesive manufacturers have used a comparison of unrestrained differential movement with the shear deformation of an adhesive at failure to predict whether the adhesive would fail in the system. This method is deficient in several respects:

1. Adhesive shear *strain* (deformation/thickness) determines failure, rather than adhesive shear *deformation*.

2. The unrestrained differential movement of a tiling system is much greater than the resulting shear deformation of the adhesive, because the tiles and substrate suffer tensile or compressive deformation when restrained. For example, in the case presented in line 2

of the Table in Appendix 2, the adhesive shear deformation is 63% of the system differential movement.

3. Studies of failed tiling systems suggest that tiling adhesive fails in a combination of shear and peel, indicating that shear strain is not the sole critical factor determining failure.

Differential movement determination

Adhesive manufacturers who are using the above shear deformation method have calculated differential movement using the length of a tile, whereas the distance between movement joints determines differential movement. These manufacturers have considered differential movement induced by heating of the tiles alone. This occurs during a transient period before the substrate is also heated. In such transient heating, the tiles are non-uniformly heated, with the outer face heated and the inner face unheated, like the substrate. As a result, a transient temperature profile is set up through the tile. For example, in Figure 14 the outer face of the tile is at 60°C, while the inner face and substrate are still at 20°C. The average temperature rise of the tile would then be near 20°C, not 40°C as assumed by the adhesive manufacturers. When the substrate begins to heat, the differential movement may reduce, because the thermal expansion coefficient of concrete is greater than that of the ceramic tile. Therefore, manufacturers applying the shear deformation method incorrectly estimate applied differential movement.

Finite element analysis

This numerical method, available in commercial computer packages, enables the stress and strain distribution in a tiling system to be determined for given differential movement and assumed material properties. The computation is substantial even where only elastic material properties are considered. Some results depend on the finite element grid size used. Actually, the plastic and viscous properties of the adhesive need to be considered to predict adhesive failure. Furthermore, it should be recognised that many failures will tend to occur due to an irreversible process of localised bond failure where there is a progressive reduction in the total bonded area.

However, even assuming elastic properties, results can be quickly obtained for the effects of changes in system parameters, showing propensity to failure. These trends have been found to differ between uniform tile expansion [13] and non-uniform tile expansion (from transient heating) [27], but mixed modes of differential movement are likely to occur in practice. When one considers all of the possible sources of movements, the inherent differences in material properties, and the potential variations arising from differences in construction techniques and installation practices, one can appreciate the enormity of the problem of predicting the performance of tiling systems. However, given this level of complexity, the best approach appears to be to determine the influence of distinct aspects of the overall behaviour, before developing a composite model to understand a particular situation.

Physical experimental model

The maximum stresses predicted using FEA with elastic properties can be used to predict failure when a physical experimental model similar to the tiling system is tested to failure and similarly analysed [20], as detailed in Appendix 1.

The standard adhesive shear test does not provide a similar experimental model, because it is loaded by force, producing a combination of shear and tensile stresses different from that produced by direct differential movement, as occurs in a tiling system. Hence a practical physical experimental model for use in predicting adhesive failure in tiling systems remains to be devised.

In this context, it is worth noting that since the tensile stress on the tile surface is not uniform (Figure 6), the use of strain gauges to determine the stresses occurring within tiling systems, as used in Refs [15, 28], might be influenced by the location and orientation of the strain gauges.

CONCLUSIONS

Partial analytical approaches can be used to estimate the shear stress concentrations in tiling systems, but are presently inadequate for predicting peel stresses. Therefore, FEA becomes necessary for predicting all the stresses that occur within tiling systems and their concentrations, particularly in the critically loaded regions of tiling runs.

At the present stage of progress in the finite element modelling of tiling systems, it is to be expected that particular investigations will concentrate on specific aspects of the overall complex composite problem. Thus McLaren *et al.* [26] have considered systems with differential movement caused by bending of the system, while Naniwa *et al.* [25] have looked at a cross section half a tile wide in considering the effect of differential movement on a tiling system. Banks and Bowman [13, 27] have also considered differential movement, but over the distance between movement joints, finding that the stress distribution contours for uniform tile expansion [13] and non-uniform tile expansion (from transient heating) [27] are quite different; also, the adhesive stresses increase from tile to tile such that they are at a maximum close to movement joints. Such modelling allows several conclusions to be drawn about the design of tiling systems and the selection of materials. Naniwa *et al.* [25] have obtained data that can be used to improve the design of external wall tiling systems. McLaren *et al.* [26] were able to demonstrate the role of the grout joints in the failure sequence that occurs when a floor bends. They showed that the design rules for traditional cement-based adhesives should not be applied to recently developed polymeric adhesives, and suggested several modifications to the design guidelines. Thus, while the approaches taken have been very different, all of them are useful as each has provided further insight into a specific aspect of the overall (highly complex) problem.

While partial analytical methods can be used to obtain an indication of the likely adhesive shear stresses, one has to be very aware of the assumptions that have been made and the limitations that thus apply. Such methods may provide more cost-effective solutions in some circumstances. Assumptions also have to be made with respect to finite element modelling, and there are again limitations that one must recognise. One must complement the FEA with tests to failure of a physical experimental model, but such procedures have still to be fully developed. FEA can assist in product development as it provides a means of rapidly and cost-effectively determining the relative effect of modifying a system parameter, prior to confirmatory testing. A better knowledge of the time-dependent behaviour of the system components will allow development of more reliable models, assisted by the continued development of more powerful finite element software.

FEA indicates that there is a potential deficiency in draft European Norms for ceramic tiling adhesives since they do not require the determination of the shear strength of cementitious adhesives, or the tensile strength of dispersion adhesives. The logic for this is hard to determine given some of the conclusions that can be drawn from the modelling of tiling systems.

The identification of locations where critical stresses will occur is important, because one can take particular care to ensure that best work practices are followed at these locations. However, this is only a partial solution.

Analysis of the stresses in adhesive joints is essential for efficient design, particularly if realistic factors of safety are to be used. In the design process it is important to know unambiguously the mechanical properties of the materials used. Adhesive manufacturers" product literature often extols their technical virtuosity. Sadly, their contributions to the scientific literature are inconsistent with these raised consumer expectations. If consumers are to realise their expectations of improved life cycle performance, more information must be made available to designers. This should instil greater confidence in architects, and enable tiles to be more widely used in applications such as high-rise external facades.

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APPENDIX 1: METHOD FOR FAILURE PREDICTION IN TILING SYSTEMS (AFTER [20])

This method requires the assumption of the particular peak stress in the tiling system causing failure of the system. Making this assumption is assisted by the inspection of failed cases of the tiling system. A physical experimental model of the tiling system is constructed that uses the same materials as the actual system. Also, if the peak stress assumed to cause failure is "singular", then its strength (defining peak sharpness) is made the same in the model and the actual system. Considering system loading from differential movement and/or bending effects, it follows that for the model (m) and actual system (as):

(a) The failure peak stress (the actual peak stress for the failure loading) is the same, thus:

$$\{\text{actual peak stress for failure loading}\}_m = \{\text{actual peak stress for failure loading}\}_{as} \quad (1)$$

(b) The ratio of actual peak stress for loading L to the linear-elastic FEA (LE-FEA) predicted peak stress for loading L is the same, where loading L is any given loading, thus, from (1) and (b):

$$\{\text{LE-FEA predicted peak stress for failure loading}\}_m = \{\text{LE-FEA predicted peak stress for failure loading}\}_a \quad (2)$$

(c) The LE-FEA predicted peak stress at failure loading is given by:

(LE-FEA predicted peak stress for loading L) (failure loading) / (loading L);

thus, from (2) and (c):

$$\{(\text{LE-FEA predicted peak stress for loading L}) (\text{failure loading}) / (\text{loading L})\}_m = \{(\text{LE-FEA predicted peak stress for loading L}) (\text{failure loading}) / (\text{loading L})\}_{as} \quad (3)$$

Therefore, the predicted failure loading of the actual system is given by:

$$(\text{failure loading of model}) \times \frac{(\text{LE-FEA predicted peak stress of model for loading L})}{(\text{LE-FEA predicted peak stress of actual system for Loading L})}$$

where the same FEA grid size is used in the LE-FEA of the model and the actual system.

There is a need to gain experience in applying the method to tiling systems. This will involve designing and conducting experiments suited to representative tiling systems and LE-FEA.

APPENDIX 2: CORRECTIONS TO «PREDICTION OF FAILURE SYSTEMS» [13]

1. Stresses for 3 mm adhesive-layer thickness

For the 3 mm adhesive-layer thickness, a FEA grid size of 2 x 1 mm was used instead of the 2 x 0.5 mm size indicated in Table 1. The FEA determinations for this layer thickness have been repeated with the indicated grid size, increasing adhesive peel and compressive stresses significantly. The corrected results are shown in the revised Table 2 given below. The effect of change in adhesive-layer thickness is no longer qualitatively the same in results from both FEA and CSA for adhesive compressive stress. Therefore, the effect of changes in system parameters on this stress cannot be inferred from CSA results. Also, the reduction in adhesive peel stress from halving adhesive-layer thickness for the low-modulus adhesive is no longer small, but smaller than for the moderate-modulus adhesive.

Corrected Table 2

Maximum stresses (3D) in the representative ceramic floor tiling system (Table 1), with complete adhesive coverage, 0.03% tile moisture expansion and 0.01% substrate shrinkage.
Results from FEA in bold type; *results from DSA in italics*; and (results from CSA in brackets)

Movement joint spacing (m)	Adhesive Modulus E (MPa)	Adhesive Layer thickness (mm)	Adhesive stresses Shear (MPa)	Adhesive stresses Peel (MPa)	Adhesive stresses Compressive (MPa)	Tile surface tensile stress (MPa)	Grout compressive stress (MPa)
1.215	25.0	6.0	*0.325*	(0.143)	(0.689)		*8.9*
		3.0	**0.533** *0.469*	**0.637** (0.235)	**1.119** (1.132)	**1.16**	**11.8** *10.3*
		1.5	**0.799** *0.665*	**0.288** (0.355)	**0.980** (1.708)	**1.13**	**12.6** *11.1*
	1.25	6.0	*0.034*	(0.005)	(0.022)		*1.3*
		3.0	**0.074** *0.064*	**0.103** (0.012)	**0.134** (0.057)	**0.29**	**2.8** *2.3*
		1.5	**0.134** *0.113*	**0.077** (0.028)	**0.132** (0.137)	**0.35**	**4.8** *4.0*
4.851	25.0	3.0	*0.462*	(0.252)	(1.215)		*10.9*
1.215			*0.469*	(0.235)	(1.132)		*10.3*
4.851	1.25		*0.103*	(0.050)	(0.241)		*9.7*
1.215			*0.064*	(0.012)	(0.057)		*2.3*

2. Modulus E of equivalent tile in DSA

The modulus E of the equivalent tile (combining tiles and grout joints) used in DSA depends on the number of tiles in a tile run, because the number of grout joints is one less than the number of tiles. The value of equivalent tile modulus used in the paper (15.8 GPa) applies for a tile run with very many tiles. For the tile run with four tiles analysed, the equivalent tile modulus is 5.5% greater, and the stresses predicted by DSA are greater by up to the same proportion for the moderate-modulus adhesive. For the low-modulus adhesive, the predicted stresses are greater or less by up to a few per cent. The corrected stresses are given in the above table.

3. Movement joint width and spacing

The movement joint width used was 6 mm, instead of the 3 mm indicated in Table 1. A check in one case showed that reducing this width from 6 mm to 3 mm had a negligible effect on the maximum values of all stresses, except tile-surface tensile stress, for which the maximum increased by 2.6%. The movement joint spacing has been corrected in the above table.