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תוכן עניינים

ד"ר עופר לוי- חקר כשל בחיל האוויר – יכולות פרקטוגרפיה כמותית

Failure Analysis in IAF - Quantitative fractography capability

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The IAF Failure Analysis Department conducts failure analysis for all IAF equipment failures and technical investigations at air crashes. During the investigation of a Bell AH-1 helicopter crash in 2013, a fatigue crack was identified at the tail rotor blade. As part of the investigation, it was vital to understand the duration of the cark propagation. This was achieved by quantitative fractography.

Failure analysis is a process, occurring after an event, whose purpose is evaluating the root cause of the failure. The motivation is to prevent the occurrence of similar events (or others) in the future. Failure analysis includes two major steps: first, examination and documentation of findings including fracture surface fractography which usually leads to failure mechanism determination, and second, additional inspections and tests which allow for the determination of the root cause.

When the failure mechanism is fatigue a simple determination of the root cause isn't sufficient for effective prevention of such failure in the future. To achieve effective prevention of fatigue failures it is necessary to understand the time to failure of the part. This time is represented by the number of load cycles that propagated the crack to final failure.

Quantitative fractography is a method by which the number of load cycles is estimated through examination of the fracture surface at points along the direction of the fatigue crack propagation. At each examined point the number of fatigue striations is determined, and the total number of cycle is extrapolated by examining the entire length of the fracture.

It is important to note that this method solely estimates the crack propagation number of cycles and doesn't account for the initiation load cycles.

Several experiments were conducted, later on, to determine the ability and the accuracy of this process. A uniform cycling load was applied to a specimen (according to ASTM E647-99), the number of loads for crack propagation was measured. The fracture surface was examined and the total number of striations was estimated. On average there is a 50% difference between the striation count of the fracture surface and the number of cycles applied. The experiments demonstrated a consistent result of the capability to estimate a minimal number of load cycles for the crack propagation.

פרופ' לזלי בנקס סילס- קריטריוני כשל לסדקים בממשק בין שכבות

FAILURE CRITERIA FOR AN INTERFACE DELAMINATION

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A delamination along an interface between two dissimilar, unidirectional, fiber reinforced plies of a cross-ply is considered. Failure criteria for this case have been presented in the literature. Criteria have been based upon the stress intensity factors K_1 and K_2 or the interface energy release rate $\mathcal{G}_i$ together with a mode mixity phase angle ψ. Thus, two parameters are required to predict failure. Several criteria will be presented. The parameter $\mathcal{G}_i$ is an invariant and does not depend upon a length scale; the parameter ψ does depend upon a length scale. Recently, a second invariant parameter L_1 has been defined. This

פרופ' דניאל וגנר- תכונות קיצון תלויי ממד במתיחה של דבקים אפוקסיים

EXTREME SCALE-DEPENDENT TENSILE PROPERTIES OF AN EPOXY RESIN

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Epoxy *Size effects* *Mechanical properties*

Materials with reduced size and dimensionality such as thin fibers and films, nanotubes and nanowires, or metallic clusters often exhibit exceptionally high mechanical properties compared to those of corresponding macroscopic specimens. Epoxy is an archetypal brittle amorphous isotropic polymer, which means that when stressed under a tensile force, its deformation is linear and elastic up to failure. However, thin epoxy fibers prepared in our laboratory (with a diameter in the 20-150 μm range) exhibit a striking plastic (non-elastic) behavior. This plastic deformation is accompanied by necking, a sudden prominent decrease in local cross-sectional area, a phenomenon which is almost never-observed in highly cross-linked glassy polymers. Enormous increases in all mechanical properties (Young's modulus, strength, strain, toughness) are observed in the fibers and the necked fiber segments, compared with bulk epoxy specimens. This is especially true at the smallest fiber diameters. Size effects for the strength of epoxy can be elucidated in principle either by means of a classical fracture mechanics argument (strength ~ $1/d^{1/2}$), or via a stochastic model argument (strength ~ $1/d^{1/\beta}$, where β is a function of the material and is generally larger than 2). In both models the presence and size of critical defects plays a key role. However, defects cannot explain the colossal ductility (plastic deformation) seen in our experiments, nor can the presence of defects justify a size effect in an elastic property, namely Young's modulus. Scarce evidence exists in the literature for similar (milder) size effects in epoxy fibers but without any structural justification. We find here that highly cross-linked necked epoxy fibers exhibit macromolecular anisotropy which likely explains the observed high mechanical characteristics. Could the ductility, necking behavior, and size effect in highly cross-linked epoxy fibers be attributed to macromolecular re-alignment? This is a highly counterintuitive conjecture because unlike semi-crystalline polymers, or even lightly cross-linked polymers, epoxy is an amorphous polymer which forms 3D rigid interconnects when cured, thus a macromolecular network with very little propensity to flow. Despite this apparent conceptual obstacle, first evidence of molecular (re)orientation in an epoxy fiber was obtained by Wide Angle X-ray Scattering (WAXS). If molecular (re)orientation is indeed confirmed, an explanation/mechanism will have to be proposed for such unexpected observation. This might involve reordering of polymer segments, distortion of crosslinks, or other molecular-scale structural changes, which would favor mechanisms leading to high strength, stiffness and plasticity.

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פרופ' ג'אי פיינברג- איך סדקים הנעים בחומרים מוצקים פריכים בוחרים את מסלולם

How moving cracks in brittle solids choose their path

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Fracture, *Crack Dynamics* *Heterogeneous Materials*

While we have an excellent fundamental understanding of the dynamics of ‘simple’ cracks propagating in brittle solids, we do not fully understand how the path of moving cracks is determined. Here we experimentally study cracks that propagate between 10-95% of their limiting velocity within a brittle material. We deflect these cracks by either allowing them to interact with sparsely implanted defects or driving them to undergo an intrinsic oscillatory instability in defect-free media. Dense, high-speed measurements of the strain fields surrounding the crack tips obtained via imaging reveal that the paths selected by these rapid and strongly perturbed cracks are entirely governed by the direction of maximal strain energy density and not by the oft-assumed principle of local symmetry. This fundamentally important result may potentially be utilized to either direct or guide running cracks.

פרופ' דניאל ריטל- תגובה תחת אימפקט של מתילצלולוז הידרוג'ל תרמו-רברסבילי

IMPACT RESPONSE OF THERMOREVERSIBLE METHYLCELLULOSE HYDROGELS

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Summary Thermoreversible hydrogels, among which methylcellulose, are a special class of materials that solidify (reversibly) upon heating, contrary to most materials in use today. While such materials can mimic to some extent biological tissues in terms of mechanical properties, their yet unexeplored behavior under shock loading has led to several new and intriguing findings, such as shock-induced gelation along with a remarkable propensity to mitigate the shock energy, which makes those gels suitable for shock protection. The work reported here was performed at Technion, as a collaboration between the Chemistry (Prof. Yoav Eichen and Dr. Galit Parvari) and Mechanical Engineering Faculties (Dr. Yonathan Rotbaum).

INTRODUCTION

Thermoreversible hydrogels are a unique kind of materials that, according to their exact composition, behave like a fluid at room temperature for instance, while solidifying at 70C. They remain solid over a range of temperatures beyond which they liquefy again [1].The phenomenon, referred to as inverse freezing, is fully reversible. Those gels, such as methylcellulose (MC) are often used in the food industry as texturing additions and are thus quite cheap. As of today, inverse freezing gels have not been integrated into engineering applications. Yet, the solidification phase transformation is specially interesting since it is endothermal, thus energy-absorbing. In a different context of shock wave and impact mitigation, one finds that the "usual" protective solutions are based on two concepts. The first one consists of defeating the incoming threat, e.g. by means of hard ceramics. The second concept relies on energy absorption, e.g. through plastic deformation. Yet, those combined concepts do not take into account the elastic precursor wave that is responsible for internal organs damage (e.g. traumatic brain injury), even if the protective device is not penetrated or damaged. In other words, there is no real protection for those cases in which the "non -damaging" elastic wave is the main component of the shock, such as sports accidents for example.

In this study, we have characterized the dynamic response and shock energy mitigation capability of MC gels using a Kolsky bar setup [2] and a high-speed camera. The results of this study open the way for a new generation of shock-protecting materials with a clear orientation towards elastic energy dissipation.

EXPERIMENTAL

The investigated gel, of varying composition (5 and 10 w/o) can appear as a liquid or a solid depending on the test temperature. The quasi-static behavior is thus studied using standard equipment at "high" temperature on a solid gel [1]. For the dynamic behavior, the standard Kolsky bar setup, modified to include pressure sensitive sensors, is used in the solid state to characterize the mechanical response and rate-sensitivity of the gel. In addition, the energy mitigation characteristics are characterized in the liquid state, using an instrumented cell through which the stress wave is applied to the liquid MC gel [3]. The incident and transmitted momenta are this determined, and their ratio indicates the level of energy attenuation. All those experiments are carried out with respect to control groups consisting of water and ballistic gelatin.

The main outcome of this study can be summarized as follows. First a unique impact-gelation phenomenon is observed using high speed photography [4]. While such gelation is known to require time and temperature, the energy supplied by the shock is sufficient to cause localized gelation in a few microseconds. Being an endothermic phenomenon, it is surmised that this gelation is responsible for the energy absorption described next. The second result is the quantification of momentum attenuation and its frequency dependence (MOM).

CONCLUSIONS

Methylcellulose hydrogels have been investigated for the first time for their shock response. Those gels have a surprising capacity to mitigate the incoming shock energy, most probably in relation with the discovered shock-induced gelation phenomenon. As such, it is believed that those materials could be suitable additions to bodily and structural protective systems with a clear orientation towards mitigation of traumatic organ injury.

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מר עידו סימון- חיזוי כשל בהפרדות הדבקה של שכבות מרוכבות מודבקות משניות

Debonding Failure Prediction of Secondary Bonded Composite Laminates

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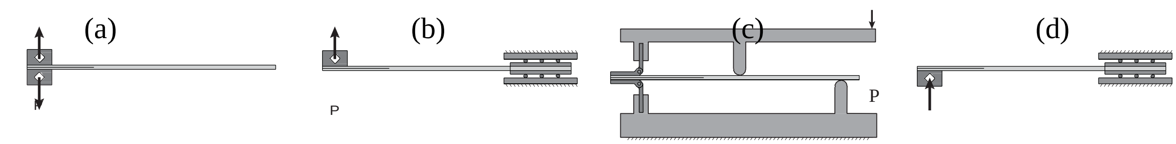
In this study, a novel numerical method to predict delamination failure in a secondary bonded unidirectional (UD) CFRP pultrusion laminate was developed and validated. The plies were precured separately before they were bonded using a room temperature curing adhesive. The numerical method was based upon a mixed mode fracture toughness criterion and an extension of a plane strain 2D special element, coded with the Abaqus FEA user subroutines.

Four types of fracture toughness tests were conducted using different beam specimens, presented in Fig. 1, to determine the pultrusion bonded laminate fracture toughness for a variety of mixed-mode I/II ratios. Double cantilever beam (DCB) tests for pure mode I, mixed mode end loaded split (MMELS) and mixed mode bending (MMB) tests for two different mixed mode ratios, and calibrated end loaded split (C-ELS) for pure mode II. The fracture toughness test data was used to determine a mixed mode fracture toughness criterion and to calibrate the special element parameters.

It was found, that the initiation fracture behavior of the beam specimens was unstable un- der all mixed-mode ratios except for pure mode II. Therefore, the special element formulation was designed to enable unstable delamination propagation. Using the suggested special element and calibrated computational model, the initial failure of the different fracture toughness beam specimens was reproduced using the FE method. An excellent correlation between the calculated and measured failure loads was achieved. However, the length of the propagated de- lamination was difficult to predict numerically. Nonetheless, the proposed numerical tool offers a fast reliable method to predict delamination failure loads in a secondary bonded laminate. This may assist structural designers in optimizing their design to reduce aircraft weight and to better understand the limitations of this type of secondary bonded laminate.

Figure 1: The different fracture toughness specimens, (a) double cantilever beam (DCB), (b) mixed mode end loaded split (MMELS), (c) mixed mode bending (MMB) and (d) calibrated end loaded split (C-ELS).



ליאור בכר- ניטור בריאות בתמסורות גלגלי שיניים באמצעות חיישני FBG אופטיים

Diagnostics of Gears Transmissions via Optic Fiber Bragg Grating Sensors

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Gears Diagnostics PHM Strain Signature

Most of the diagnostics approaches for health monitoring in gears transmissions, to date, are based on vibrations signals, as measured from piezoelectric accelerometers. These sensors are conductive and sensitive to electromagnetic interference. Here we suggest a new diagnostic methodology based on optic strain Fiber Bragg Grating (FBG) sensors. FBG sensors allow strain measurements for health monitoring, since they are immune to electromagnetic interference, flexible and lightweight. We validate the feasibility of using optic FBG strain sensors for diagnostics of three different types of gears transmissions: spur gear, helical gear and helical bevel gear. One of the greatest challenges is sensing the strain wave excited by the gear. The strain measurements for the spur gear were collected from a special test rig, where the FBG strain sensor was mounted on the bearing house [Fig.1]. The helical gear is a part of an industrial gearbox and the helical bevel gear is a part of the intermediate gearbox (IGB) of the Apache helicopter. For both gearboxes, the FBG strain sensors were mounted on the outer case. For all cases, the expected signature of the gear was noticed, e.g. the gear mesh frequency and the FM sidebands. The expression of tooth face faults (TFF) of different severities was examined for spur gear. The effects of the fault were noticed in the synchronous average signal, and the total spectral energy of the FM sidebands was affected by the presence of the fault, as expected. The feasibility of using FBG strain sensors on different gears transmissions, as well as the ability to monitor faults at different severities by both the analysis of the synchronous average and the spectral analysis, suggest that optic FBG strain sensors can be utilized for gears diagnostics applications. The foothold of strain sensors in the field of gears health monitoring may shed a new light on the physical phenomena and improve the detection capabilities.

שגיא חן- חקר נומרי של התחברות חללים ברמה המקרוסקופית בחומרים משיכים

A Numerical Study of Void Shear Coalescence at the Microstructural Level in Ductile Materials

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Keywords: shear-coalescence, ductile damage, GTN-NH

The urge for strong and lightweight materials will always be part of our everyday life. With that, one essential requirement lies in their strength and high resistance to damage. The advanced equipment in research labs, such as sophisticated microscopes and high-performance computers, allows to study the origin and the evolution of damage in metals. Specifically, the dimpled fracture surfaces observed in a post-mortem investigation of the ductile fracture indicates that the fracture had formed through coalescing voids that originated at the microstructural level. The damage process is commonly described by the nucleation and growth of those voids, thinning the inter-void material ligaments, ultimately leading to final fracture. The widely used GTN (Gurson-Tvergaard-Needleman) model for ductile fracture describes the damage growth in the scenario of hydrostatic loadings, whereas the response to shear deformation remains elusive.

In the present study [1], [2], a spherical/circular empty void is assumed to be the elementary representative feature of ductile damage. Using periodic cell calculations and the GTN-NH as the damage model (extension of the GTN model to describe void shearing, introduced by Nahshon and Hutchinson [3]), plane strain and plane stress configurations are systematically investigated, as a realization of the ligament thinning, wherein the void surroundings and the intervoid ductile ligament undergo an idealized gradual transition from plane strain to plane stress as the ligament gets increasingly thinner. The final stages of the ductile fracture process will be discussed, focusing on shear deformations to address the shear coalescence phenomenon. Emphasis will be given to the shape of the void [4] and to the local accumulated damage at the void's surroundings.

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קרול רודריגס- כוונון של חוזק וחסינות שבר של חומרים משורייני סיבים על ידי טופוגרפית הסיב

Strength and Toughness tuning of Fibre-Reinforced Composites through Interfacial Topographical Obstacles

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Fibre reinforcement *Interface* *Beaded fibre*

Natural composites display a superior balance of strength, toughness and resources through hierarchical design strategies that rely on the shape and arrangement of constituents in the composite rather than chemical means only. The presence of internal interfaces plays a particularly important role in this balance by governing toughness and deformation through non-linear deformations that channel cracks through configurations that ultimately arrest crack propagation. Implementation of such a concept, namely the incorporation of structural obstacles at the interface of synthetic fibre-reinforced composites, could be a promising way forward to simultaneously stronger and tougher engineering materials with tuneable properties dependant on the topography of the interface.

Bearing this in mind, a novel structural design for interfaces is proposed – one comprising of an array of cured polymer beads around and along the length of a fibre. The beads are proposed to act as intermittent topographical obstacles to simultaneously generate toughness and strength in fibre-reinforced composites through two main mechanisms - (1) anchorage of fibres to increase stress transfer and (2) improved resistance to crack propagation through increased pull-out resistance. Single fibre pull-out tests performed on model glass fibre–epoxy bead system support this hypothesis. The maximum fibre strength was achieved for beaded fibres under stress as compared to regular fibres without such obstacles. Pull-out of beaded fibres appeared to dissipate more plastic deformation energy compared to that of regular fibres.

The system has the potential to be highly tuneable. The polymer beads are formed by the Plateau-Rayleigh instability, through which successful control of the bead parameters (size, angle, spacing) has been achieved. An investigation into optimisation and fine-tuning the system is currently being conducted and results will be discussed.

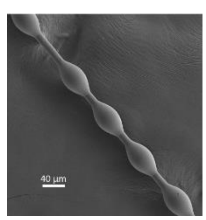

Figure 1 *- Intermittently spaced epoxy beads on fibre*

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לשכת המהנדסים האדריכלים והאקדמאים במקצועות הטכנולוגיים בישראל

ד"ר אברהם ברוט- סקירת כשל בשלמות המבנה של מטוסים מסחריים וצבאיים

Threats Against the Structural Integrity of Commercial and Military Aircraft

A survey was performed concerning structural failures of several commercial and military aircraft. The cause of each failure was identified, and should be used to avoid similar failures in the future.

ד"ר עוז גולן- סימולציות מכאניות באמצעות מיקרו-CT כשיטה אפקטיבית בחקירת כשלים ובניתוח מבנים

ד"ר עוז גולן, אפקה- המכללה האקדמית להנדסה בתל-אביב

בעבר, השימוש בסימולציות מכאניות המבוססות על אלמנטים סופיים הכריח בניה גראפית של מודל קאד והפעלת רשת חישובית (Meshing) לצורך אינטרקציה בין האלמנטים. בשנים האחרונות נכנסה טכנולוגיה חדשה המבוססת על סריקת מיקרו-CT ועל אלמנטי נפח הקרויים ווקסלים (Voxel). היתרון של שיטה זו הוא בפשטות שלה ובאפשרות לבצע סימולציות מהירות לאלמנטים מיקרונים ברזולוציה גבוהה ללא צורך בכושר מחשוב גבוה. מבנים כמו לאטיסים או מבנים מוקצפים, אשר היו בעבר קשים לסימולציות מכיוון שגרמו לקריסת מחשבים, נעשים כיום קלים לאנליזות עבור המהנדסים המכאניים בזכות הטכנולוגיה החדשה.
מערכת מיקרו-CT חוסכת את מידול האובייקט במיוחד במבנים המסובכים גיאומטרית. המודל התלת ממדי שמתקבל באמצעות הרכבה של תמונות דו-ממדיות (רקונסטרקציה) מאפשר לצפות בתוצאות הסימולציה בכל חתך לרבות בידוד אובייקטים לפי צפיפות או לפי גיאומטריה (סגמנטציה). תוכנות אנליזה מתקדמות מאפשרות ביצוע של אנליזה גיאומטרית ובקרת מידות ומעניקות למהנדס המכאני כלי רב עוצמה שמסייע לתכנון המכאני ולחקירת כשלים.
בחקירת כשלים קיימת חשיבות רבה לפגמים ולהשפעתם על התכונות המכאניות של המוצר המוגמר. פגמים יכולים להופיע בצורת פורוזיביות או חוסר התכה בהדפסה תלת ממדית, אינקלוזיות ביציקות, חוסר רציפות בסינטור או בריתוך וכו'. נדבך נוסף קשור למותאמות הגיאומטרית בין התכנון (נומינלי) לייצור (אקטואלי), כמו גם לטיב פני השטח ולהשפעתו על תוך החומר. התוכנות המתקדמות של מערכת ה- CT מאפשרות ביצוע סימולציות מכאניות עם פגמים וללא פגמים בהתאמה. כלומר, השפעת הפגמים על המאמצים ומציאת נקודות כשל פוטנציאליות (בעזרת hot spots analysis) של ריכוזי מאמצים, התחלת סדקי התעייפות וכו'. התוכנה מסוגלת להשוואות בכל חתך בין הסימולציות המתקבלות מקובץ התכנון (אקטואלי) לבין אלו של האובייקט הסרוק (נומינלי) ע"י הלבשתם יחדיו וחישובי אנליזות על הדלתות (□) של וון מיזס / מאמצים ראשיים / תזוזה וכו'.
במכללת אפקה קיים מתקן ייחודי המאפשר סריקת CT של אובייקטים תחת עומס ובכך ביצוע וולידציה בין הסימולציות המכאניות למציאות וכן ביצוע חקר מנגנוני כשל ברמה מיקרונית.
במהלך ההרצאה נביא דוגמאות לחקירות כשל ואנליזות שמבוצעות עבור התעשיות בישראל.

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ד"ר שי פלדפוגל- התקדמות סדק בממשק משתנה שכבתית

Non-self-similar interface crack propagation in layered plates

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Plate-like interface crack *Unstable debonding* *Bonded tiles*

Adhesively bonded layered plates are ubiquitous in modern structural and mechanical applications. The failure mechanisms of these systems always involve some degree of interfacial cracking (debonding). A pure interfacial mechanism typifies an age-old and prevalent layered form, namely adhesively bonded tiles. The inherently two-dimensional, geometrically irregular, and non-self-similar nature of the debonding evolution in bonded tiles raises essential questions: how does the two-dimensional debonding region change in size, location, and shape as the load levels increase? is the growth of interfacial cracking a stable process or an unstable one? how does the tile geometry affect the mechanism's evolution? what are the debonding-triggering loading levels? The objectives of this paper are to address these pertinent questions.

The main challenges in addressing the raised questions are the geometrically irregular and non-self-similar interface crack evolution; the 3D interfacial traction state; the presence of a relatively soft intermediate layer sandwiched between the substrate and tile layers; and the orders-of-magnitude difference between the length-scales that govern the interfacial interactions and those of the system's lineal dimensions. To face these challenges and address the pertinent questions, specially tailored multilayered plate theory and a corresponding triangular finite element are developed. The formulation combines extended high-order plate theory, plate-like cohesive interfaces, a pseudo arc-length solution procedure, and a mode decomposition technique that alleviates shear locking.

A numerical example considers the interface crack propagation in a single bonded tile under uniform heating. This simple configuration allows studying the interfacial failure and characterizing it in pure form. Emphasis is placed on the relations between the non-self-similar crack propagation and the stability features of the interfacial mechanism. Fig. 1 shows contour maps of the interfacial peeling traction that represent the interface crack fronts in a rectangular tile. It can be seen how the crack nucleates at the corners of the tile (a), starts to propagate inwards along the short sides and coalesces at their centers (b), further propagates inwards along the long sides and coalesces at their centers (c), and becomes circular at the final stages of the process (d). Figure 1 demonstrates the inherently geometrically irregular and non-self-similar crack propagation, as well as the numerical model's capacity to capture and follow it.

In addition to the kinematics of the crack propagation, the full paper considers it in conjunction with the structure's equilibrium path (a graph of the debonded area plotted against the thermal load). This allows elucidating the relations between the interfacial mechanism's kinematics and the stability in the different phases. It is found that: (a) the interfacial failure is adhesively bonded tiles in inherently brittle and unstable; and (b) crack calescence is invariably associated with the triggering of interfacial instability, strongly linking the kinematics and the stability feature. Both observations underscore the significance and the effectiveness of the unique features adopted in the specially tailored methodology.

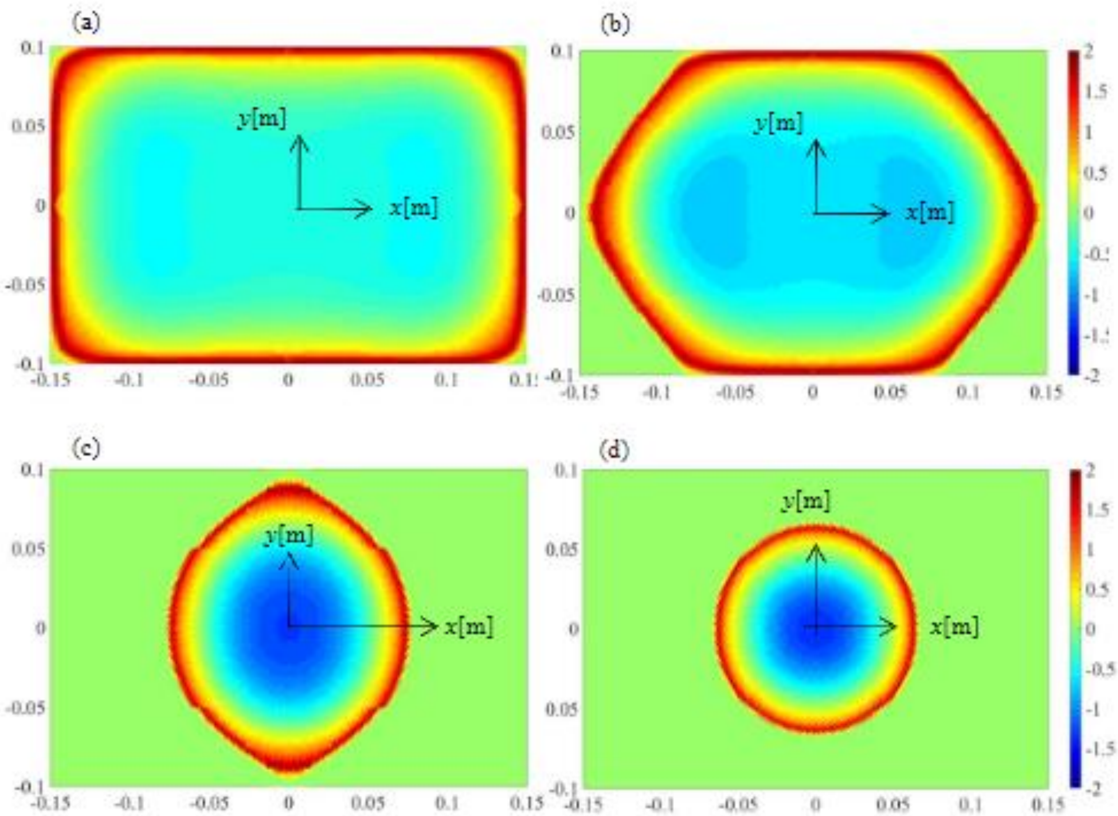

Figure 1 – *Progressive debonding fronts at the substrate adhesive interface of a rectangular tile subjected to uniform heating*

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Brittle fracture to the atomistic scale

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Fracture energy evaluations *Brittle materials* *Atomistic bond breaking*

We examined the ambiguity still existing among theoretical continuum/atomistic based Griffith theory for brittle fracture and continuum based Freund equation of motion of cracks and atomistic theories and atomistic computer simulations. These show large and fundamental gap between the energy required to initiate a crack and the initial crack speed upon initiation.

The gap between Griffith energy barrier and the much higher ‘lattice trapping’ effect barrier was investigated by experiments, atomistic simulations, theory and topological considerations. We correlate the macroscopic cleavage energy with atomistic events along the crack front.

We suggest a solution that is based on a unified driving force responsible for the whole range of cleavage energies; it is the derivative of the energy release rate (ERR), G_0, with crack length a, which we term Θ. When this variable is low, the bond breaking energy is comparable with Griffith barrier. When high, the cleavage energy approaching the ‘lattice trapping barrier’. While macroscopically Θ governs the cleavage energy, microscopically it is also responsible for the bond breaking mechanisms and sequence along the crack front.