The Simulation of Paint Cracking and Peeling

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Abstract

Weathering over long periods of time results in cracking and peeling of layers such as paint. To include these effects in computer graphics images it is necessary to simulate crack propagation, loss of adhesion, and the curling effect of paint peeling. We present a new approach which computes such a simulation on surfaces. Our simulation is inspired by the underlying physical properties. We use paint strength and tensile stress to determine where cracks appear on the surface. Cracks are then propagated through a 2D grid overlaid on the original surface, and we consider elasticity to compute the reduction of paint stress around the cracks. Simulation of the adhesion between the paint and the underlying material finally determines how the paint layer curls as it peels from the surface. The result of this simulation is rendered by generating explicit geometry to represent the peeling curls. We provide user control of the surface properties influencing the propagation of cracks. Results of our simulation and rendering method show that our approach produces convincing images of cracks and peels.

Key words: Deteriorations, surface imperfections, paint, cracks, multi-layer surfaces, natural phenomena.

1 Introduction

Cracks and peels in paint are a common everyday phenomenon. For example, after a few years of exposure to the elements, cracks appear on painted wooden doors, often resulting in peeling of the paint layer away from the underlying wood. These visual effects can be very significant (see for example the left images of Figures 8, 9, and 10), and we believe that it is important to include them in computer generated images. As with all aging and weathering effects, simulating and rendering such phenomena results in images which have a much higher degree of realism. In typical synthetic environments, used for example in films or video games, many painted objects exist as well as objects which are made from layered surfaces, and thus it is important that they include the simulation of cracking and peeling.

Previous approaches in computer graphics have either only simulated cracks and their propagation without treating multi-layer phenomena and peeling [7, 8], or presented tools to control the location of detached paint areas without treating the creation and propagation of cracks [18]. Consequently, no complete method currently exists, which allows a user to simply request the generation of cracks and peels on a surface.

Our approach is inspired by the underlying physical phenomena, but uses a simplified model. It allows a fast and simple simulation process, provides good control to obtain the desired effects, and gives convincing results.

Our current implementation operates on a planar surface, and assumes that the outer paint layer is infinitesimally thin. We generate cracks on the surface, based on the simulation of tensile stress in the paint layer. Cracks are created and propagated on the surface using a 2D grid to access local surface properties. These properties can be represented in different ways, either procedurally, as a constant, or a texture. For example, if we wish to reproduce a specific type of crack pattern, textures can be used to define surface properties. The cracks are then guided by texture value and gradient. Simple intersection of cracks is handled, and fine details of cracks are maintained separately, thus increasing simulation speed. The simplicity of our crack propagation algorithm allows us to compute a simulation efficiently, giving the user fine control and the ability to easily experiment to obtain the desired result.

In addition to crack propagation, we generate and render the curling effect of peeling on our two-layer representation based on the simulation of adhesion between these layers. To our knowledge this is the first treatment of adhesion and curling for peeling in computer graphics. This effect adds important and convincing visual detail. Curling is computed at an appropriate level of detail of the crack path as paint loses its adhesion with the underlying surface. As a result, peeling can occur in different directions as simulation proceeds, which corresponds to observed physical reality. It is important to note that we do not modify the underlying geometry to add this curling effect, but simply superimpose additional geometry on the underlying object.

The entire approach, crack propagation and peeling, is relatively simple to use with standard rendering packages.

2 Previous Work

Simulating "imperfections" or "weathering" is a relatively young area in computer graphics. To our knowledge, the first such approach was that of Becket and Badler in 1990 [2] which described a general system treating scratches, stains, splotches, and rust.

Dorsey and colleagues have developed a series of methods treating a number of different phenomena, such as patinas, weathering due to flow of liquids, and weathering of stone (a survey is presented in [5]). These models are typically based on involved physical simulations, with relatively expensive computation times and the need to determine physical parameters. Such models are indispensable for correct and accurate simulation of weathering phenomena, and have produced images of striking realism and beauty. Nonetheless, their usage can be cumbersome for some applications, and more simplistic, albeit less accurate, approaches can also be useful. Approximate models can often be more appropriate, for the computer graphics industry [17] for example.

In this paper we treat generation and propagation of cracks on a two-layer model. Dorsey and Hanrahan [4] developed a model based on multiple layers to simulate metallic patinas, in the context of texture generation tools. Sophisticated shading models were used, resulting in great realism. Merillou *et al.* [10] presented a two-layer model to simulate scratches on a surface. Their approach does not add geometry to represent the scratches, but simply defines an appropriate anisotropic reflectance function to give the correct visual impression of scratches.

Another aspect of our work deals with the formation and propagation of cracks which can then peel. Terzopoulos and Fleischer [16] developed an early physically-based model of fracture, as part of the treatment of inelastic behavior in general. O'Brien and Hodgins [12] developed a model for fracture on an adaptively subdivided tetrahedral mesh. A more complete physically-based simulation is used, and cracks are propagated in 3D. This model concentrates on the dynamics and the motion of fracture, yielding impressive visual results, but at a non-negligible computational cost.

Hirota *et al.* [8] simulated cracks on a surface caused by surface contraction. Their approach is based on physics to a certain extent, and is modeled as a network of springs. Cracks appear as springs break, and thus their paths are constrained by the spring network. The nodes are squares or hexagons, resulting in different types of crack shapes. The visual quality of the cracks is directly affected by aliasing across the network cells. Neff and Fiume [11] simulated the generation of cracks due to a blast wave. A seed crack is used and cracks are propagated, releasing energy as they proceed. This enables the creation of new crack branches. A simple random variation scheme on the branching direction generates visually convincing results.

For our crack propagation method, we have been inspired by the ideas presented in Gobron and Chiba [7]. Their method however deals only with cracks and does not simulate adhesion or peeling. As with our approach, cracks are propagated across a 2D grid, using a relaxation method. Certain aspects however of their simulation are more simplistic, as their approach does not treat peeling (adhesion, curling, etc.). Since between 100,000 to a million cells are required for the simulation of their cracks, computation time is quite expensive, ranging from 20 minutes to several hours.

Finally, in the general system presented by Wong *et al.* [18], peeling is treated along with rust and dust. This approach simply modifies the surface color based on a threshold function for the choice of the appropriate layer color, and thus the geometric effect of cracks, loss of adhesion, and surface curling are not simulated. No simulation of crack creation and propagation is performed, and the user must manually position "peeling light sources".

3 Physical Basis

Paint and other thin layers are applied on many surfaces for both decorative and protective purposes. The condition of the paint layer over years of exposure depends on many factors including the paint itself (*e.g.*, latex or oil), the surface on which it is applied (*e.g.*, material such as wood or metal, roughness, penetration [9]), as well as environmental factors (*e.g.*, UV light, oxygen, pollutants). All these factors affect paint differently during its lifespan [6]. Four properties are of major importance to paint cracking and peeling: stress, strength, elasticity, and adhesion to the base surface.

One factor is inherent to every kind of paint: as paint dries, it shrinks, producing *stress* in the paint layer [13]. In this context, thinner paint layers are preferable to thicker ones since they induce less stress. A dirty or wet base surface and insufficient stirring of the paint also results in weaker paint layers [3]. The method of application (*e.g.*, brush, spray, roller) also affects the layer quality [3]. Even after paint has dried, its properties are not fixed as it will slowly become weaker because of interaction with the elements of its environment. The principal cause of damage is moisture [15], but many other environmental factors [1, 3] such as water, UV light, temperature variations (contraction or dilation of the base surface), pollutants, abrasion, and impacts all weaken the paint layer.

When paint is weakened, the physical properties of the layer change. Paint is to some extent *elastic*, that is it can be stretched thus redistributing surface stress. As years pass, the elasticity of paint is likely to decrease. Long term exposure to pollutants for example can greatly decrease elasticity. The paint also has a specific *strength*, which determines the greatest stress it can handle before it starts to break. As is the case for elasticity, exposure to harsh elements or UV light can reduce the strength of the paint, making it prone to develop cracks and peels. When a crack forms, it is readily visible since it enables the paint on either side to shrink back to a state with less stress. This release of tensile stress occurs perpendicularly to the crack [7]. *Adhesion* is the most important property of paint. We define it as the ability of paint to attach itself to the underlying surface. Moisture, base surface contraction, or rust can all greatly reduce the adhesion of paint. When the paint shrinks as cracks release tensile stress, a shearing force is introduced at the interface between the paint and the base surface, pulling the paint away from its initial position. As paint loses adhesion with the base surface, it can either peel by slowly curling away [6, 3], or flake [3] and eventually fall off the base surface.

As we can see, peeling is a complex phenomenon that spans over years. It is not fully understood, since most of the (physical) research focuses on preventing its occurrence [6]. Moreover, most of its parameters are difficult to measure. In this paper, we develop a model inspired by, rather than strictly simulating, the physics of the phenomenon. Our goal is ease of control, allowing the user to obtain effects that are visually appealing. In our simulation process, the paint strength and stress determine where cracks appear on the surface. Reduction of stress around the cracks is computed by considering the elasticity. Finally, curling of the paint layer as it peels from the surface is computed with the adhesion. In the next two sections, we detail the structures and algorithms of our empirical peeling model.

4 Simulation

4.1 Overview

Our simulation model is simple and summarized in Figure 1. A surface is defined by two layers that we will refer to as *base layer* and *paint layer*.[1] When tensile stress (Figure 1-i) is too high compared to the paint strength,

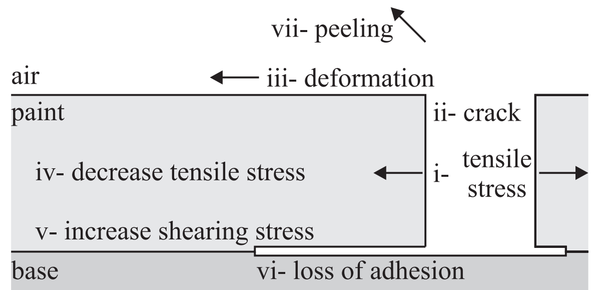


Figure 1: Peeling model.

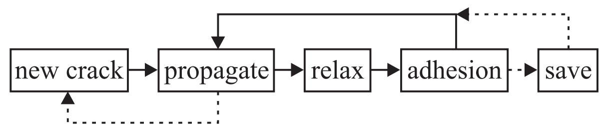


Figure 2: Simulation cycle.

a crack can appear (Figure 1-ii) and expand on the paint layer according to the local surface properties. By allowing the paint to shrink (Figure 1-iii) to a lower energy state, cracks reduce the tensile stress (Figure 1-iv) in the paint layer, producing an increase in shearing stress (Figure 1-v), and can cause adhesion to the base layer to be lost (Figure 1-vi). Thereafter, the paint is free to peel away from the base layer (Figure 1-vii).

Our simulation process is presented in Figure 2. Several cracks evolve on a surface and can intersect each other. To produce an image, the cracks and their parameters are passed to the rendering module (described in Section 5) where their shape is computed and rendered. This can be done at the end of the simulation or at time step intervals.

The surface properties are represented by a 2D grid structure. Each grid cell stores its local paint properties (adhesion, stress, etc.) and bilinear interpolation is used to compute properties for any location on the surface. Every surface property can have a value that varies with respect to direction on the surface. We represent such directional variations by storing samples for a predefined number of directions.[2] The resolution of the grid is responsible for many features (propagation speed, crack details, efficiency, etc.) that will be explained in the next sections.

Cracks propagate on the surface and are represented

[1] While the top layer can be of a different material than paint (*e.g.*, wallpaper), it is simpler to refer to it as paint.

[2] Since these properties are symmetrical, they need to be stored only within 180^o. We typically use four directions ($0^o, 45^o, 90^o, 135^o$).

Paint Properties	Units	Source	Use
σ Tensile stress	force / length	user specified	creation, propagation, relaxation
S_b Tensile break strength	force / length	user specified	creation
S_c Tensile crack strength	force / length	user specified, $S_c < S_b$	propagation
δ Tensile deformation	length	$\delta = \sigma.cellSize.(1 - \frac{distance}{D_r})$	relaxation
D_r Elastic relaxation distance	length	user specified	relaxation
τ Shearing stress	force / length	$\tau = \delta / cellSize$	adhesion
S_a Adhesion strength	force / length	user specified	adhesion
Crack Properties			
W_c Crack width	length	$\sum \delta_i$	rendering
W_a Adhesion width	length	$distance$	merging, rendering

Table 1: Paint and crack properties. The equations are simple so their effect is intuitive to understand. All the user specified properties can be constant or vary over the surface. Constant terms should be added in the equations of δ and τ so that the units match, but were not included for clarity.

by connected segments forming piecewise linear curves. They are independent of the 2D grid representation which only serves to query the local surface properties. Typically, crack segments are smaller than the grid cell size. The surface and crack properties used throughout Sections 4 and 5 are presented in Table 1.

4.2 New Cracks and Propagation

We assume that if nothing else held it in place (*e.g.*, neighbor cells, adhesion to base layer), the paint layer in a cell would shrink to a stable lower energy state. The *tensile stress* σ is the difference in energy (force) between the current state and the stable state of the paint layer. The *tensile break strength* S_b is the maximal force the paint layer can handle before it breaks. Thus, if the stress σ exceeds the strength S_b, the paint will break. A new crack appears within the grid cell with the highest stress to strength ratio σ/S_b (Figure 3(a)).

The creation and propagation of cracks are strongly influenced by the stress and strength properties of paint. These properties can be dependent on the direction on the surface. For instance, wood fibers in the base layer can induce directional variations in stress and strength. When creating a crack, the orientation of the initial segment is perpendicular to the orientation of the maximal stress to strength ratio σ/S_b. Since we represent the directionality with samples for fixed directions, we use random distributions based on the sample values to compute the orientation of the maximal value of a property.

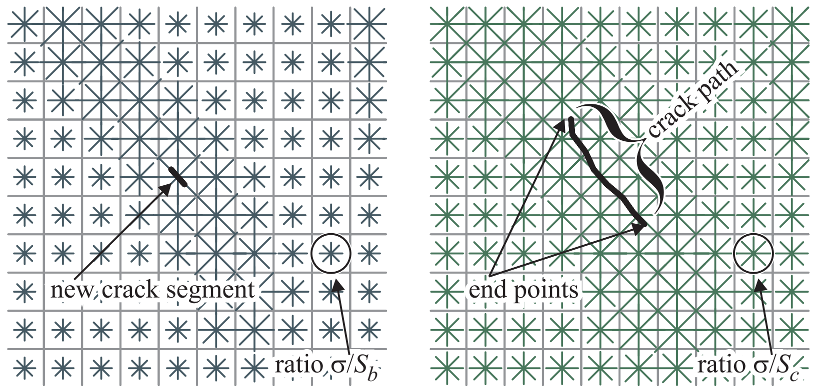
A propagation step moves each crack end point by a linear segment of length smaller or equal to the grid size, thus guaranteeing that we do not miss any grid cell contribution along this segment (we typically use a uniform distribution between 0.5 and 1.0 times the grid cell size). This propagation defines the path followed by a crack (Figure 3(b)). When propagating cracks, the stress σ is compared to another paint property, the *tensile crack strength* S_c. A crack stops when the local stress σ is below the strength S_c, or when it intersects another one (see Section 4.5). As when computing the orientation of new cracks, each of the two end points of a crack has a tendency to propagate in the direction perpendicular to the local highest stress to strength ratio σ/S_c. We also mix the computed orientation with the previous crack direction to prevent changes in direction which are too abrupt.

The top arrow in Figure 2 presents the main simulation loop, showing how the cracks and paint are adjusted in each step. We propagate the cracks until extinction of movement, before creating a new crack (bottom arrow in Figure 2). This simulates the fact that it often requires less energy to propagate a crack than to create a new one [14]. It also prevents the creation of many separate cracks within regions of high stress, and results in more continuous and realistic cracks. This strategy also greatly reduces the number of intersections that must be computed. In the same spirit, our crack strength S_c is lower than the break strength S_b to ensure that cracks will not stop after only a few propagation steps (we typically use a S_b that is equal to 1.5 times S_c).

4.3 Relaxation of Tensile Stress

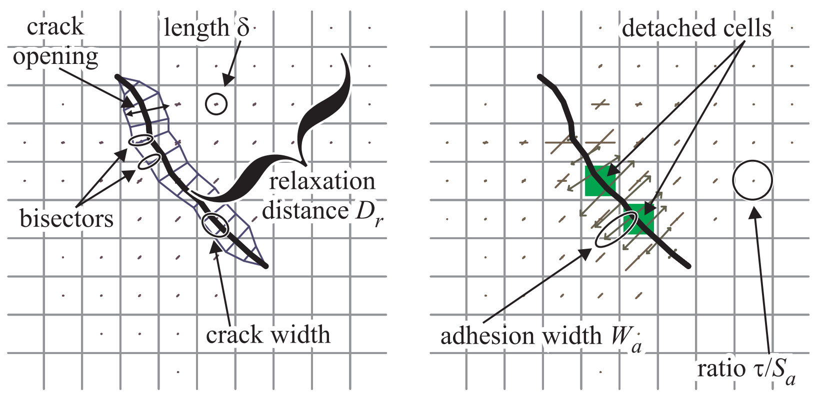
As we saw in Section 3, cracks reduce tensile stress in the paint layer. We simulate this relaxation process by reducing the tensile stress of the cells close to each crack segment.

The *elastic relaxation distance* property D_r determines how far from the segment we should release stress. A *tensile deformation* δ of the paint layer, corresponds to the release in tensile stress. This is shown in Figure 4(a) for each cell. The amount of deformation (and stress re-



(a) (b)

Figure 3: Snapshots from our system for creation and propagation of cracks. (a) The initial stress to strength ratio σ/S_b scaled such that a ratio of 1.0 corresponds to the size of a cell and presented as lines for the four sampled orientations. A new crack is created perpendicular to the maximal ratio. (b) The propagation of a crack (note that $\sigma/S_c > \sigma/S_b$ and that no relaxation was computed on the stress σ used to compute the presented ratios).



(a) (b)

Figure 4: Snapshots from our system for relaxation and adhesion. (a) The cumulated deformation lengths δ caused by the relaxation. The bisectors on both sides of the crack represent the crack width and determine the region affected by each segment. (b) The shearing stress to adhesion strength ratio τ/S_a. Grey cells have lost adhesion to the base layer, and arrows on each side of the crack represent how far adhesion to the base layer is lost with respect to the crack.

lease) decreases linearly from the crack segment to the user specified relaxation distance D_r.

The paint tensile stress released by a crack should be roughly perpendicular to the crack. The direction of relaxation for a point on the paint layer is interpolated from the two bisector vectors for each segment (see Figure 4(a)). Compared to Gobron and Chiba [7] where only the direction perpendicular to the segment is considered, our approach avoids unwanted overlap (when consecutive segments form a concave curve) or cells that can receive no relaxation (in the convex case).

The set of cells close to the crack end points will be used to compute the paint tensile stress on the next propagation step. Since they will serve in the crack propagation computation, relaxing their stress would cause the crack to release stress ahead of itself. This would be incorrect with respect to the real physical phenomenon, and could cause the crack to stop for no apparent reason. These cells are thus excluded from the relaxation computation.

As described so far, the crack propagation has resulted in a set of piecewise linear segments indicating the central path of the crack. However a crack is an opening in the paint layer. As the paint layer is relaxed by the cracks, it shrinks locally by the deformation lengths δ. This causes the crack to widen, and the base layer to become visible. The deformation length δ of each relaxed cell is added to the *crack width* property of the crack segment(s) responsible for this relaxation. For each crack segment, an independent width is computed for each side of the crack. This results in two sets of corresponding piecewise linear segments with independent crack width values defining the crack sides. The crack widths are displayed in Figure 4(a) as segments on both sides of the crack path; linear interpolation is used to ensure continuity from one segment to the next.

4.4 Adhesion Modification

We next explain how we determine when curling of the peels can occur. As the paint layer shrinks by relaxation, it causes a lateral deformation of the layer, which induces a *shearing stress* τ counteracted by the paint adhesion. The *adhesion strength* S_a represents the maximal force (due to shrinking) that the paint layer can tolerate before adhesion to the base layer is broken. If the shearing stress τ increases above the adhesion strength S_a in any direction, the paint layer in this cell is considered as "detached" from its base layer for all directions. This computation only accounts for deformation local to the cell, without considering deformation of adjacent cells. It also is a binary operator, so even if adhesion to the base layer would be lost in the vicinity of the crack, when considering the whole cell, adhesion to the base layer can remain.

It should be noted that when the relaxation of tensile stress (Section 4.3) encounters cells detached from the base layer, it sums the deformation lengths δ, but extends the relaxation to a larger region by considering the detached cells as having a null size. The linear decrease of the relaxation deformation is thus moved further away from the crack, due to the loss of adhesion.

When adhesion is lost, the paint can curl away from the base layer. To compute this peeling, each crack segment keeps, in an *adhesion width*, the distance to the closest cell (with respect to the region defined by its bisectors) that is still attached to the base layer (Figure 4(b)).

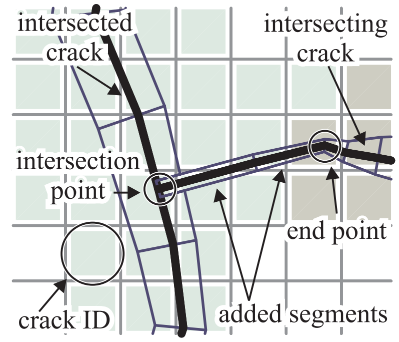


Figure 5: Intersection between two cracks, the intersected (previous) crack and the intersecting (new) crack. The identified end point corresponds to the intersecting crack end point before the intersection is detected. Cells with a light grey background are those marked by the intersected crack ID, while the cells with a dark grey are those marked by the intersecting crack.

4.5 Intersection

As a crack propagates through the grid, every cell within a distance of half a cell is marked with its crack ID. We do not allow two cracks to traverse the same cell. Independent cracks are therefore always separated by a minimal distance related to the grid resolution. Self-intersection of a crack cannot be detected by the crack ID but can be handled by separately testing for intersection of the crack with itself.

When a crack enters a previously marked cell, the new segment is guaranteed not to cross over a previous crack segment. At this point the *intersecting* crack has not yet reached the *intersected* (previous) crack (see Figure 5) but we force the new crack to intersect the previous crack, as if the weakened paint layer suddenly broke. We thus need to connect the two cracks. The intersection point is the "closest" point on one segment of the intersected crack. First we eliminate the segments of the intersected crack for which the intersecting segment end point is not contained in the space confined within the intersected segment and bisector directions. For the remaining segments, we identify their respective intersection point and keep the segment with the closest intersection point.

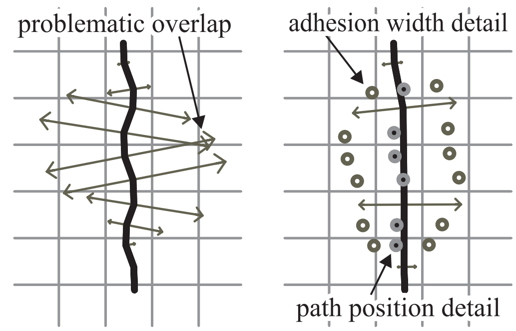
We then add two segments to the intersecting crack to connect it to the intersected crack. Elastic relaxation of tensile stress is computed with respect to the added segments to determine the crack width of the intersecting crack where the intersection occurred. After relaxation, the intersected crack is split at the intersection point with respect to the intersecting crack width. The newly formed (opened) crack smoothly joins each side of the intersecting segment.

4.6 Segment Merging and Crack Detail

As the paint loses adhesion to the base layer, elastic relaxation reaches further away from the crack and the peels also curl further. Similarly to elastic relaxation, the peels curl away from the base layer in the direction perpendicular to the crack path (in our case, the directions of the interpolated bisectors of Figure 4(a)). As the relaxation or peeling reach further away from the segment, they should consider a larger portion of the crack. The computations thus have to consider the crack at a coarser level of detail as the adhesion width increases.

As explained earlier, the crack path traverses the paint layer with changes in direction that are not too abrupt. When little adhesion is lost, the adhesion width W_a vectors (Figure 4(b)) are short and the peel will curl very locally. When the loss of adhesion extends much further, the adhesion width W_a vectors are much longer and they can even intersect each other, yielding unexpected results as illustrated in Figure 6(a). It will also be difficult to create geometry for curling such peels. We solve these problems by merging together adjacent segments. This is similar to considering the crack path at a coarser level of detail, disregarding high frequency variations of the crack path (see Figure 6(b)). Merge operations are controlled by a set of metrics that determine if segments should be merged or not. These metrics consider different factors such as the segment lengths with respect to their adhesion width, and the difference in direction between consecutive segments.

Of course, we still want to keep the high frequencies of the crack path to compute the geometry of the peels, even though we do not use them to compute the relaxation or the peels curling directions. We do this by keeping *detail* records that store the difference (in crack and adhesion widths, as well as position) between the merged segments and the coarser level segment (see Figure 6(b)). This information is used when generating the geometry and for rendering the final peels.



(a) (b)

Figure 6: Merge of segments at a coarser level of detail. (a) Before merging, the peeling regions of some segments overlap. (b) After merging and recomputation of the adhesion widths, peeling regions respect the linear behavior of the crack path. The detail records for the crack path position (black dot on grey circle) and the adhesion width (white dot on grey circle) are also shown.

4.7 Interaction

We implemented this technique in an interactive system in which the user can specify the different properties and simulation parameters. Running on an Octane2 with a MIPS R12k 400 MHz CPU, the propagation is interactive (many new segments per second) for up to about 30 cracks. This enables the user to observe the evolution and change the parameters early in the simulation process.

The specification of paint layer parameters can be done with properties constant over the entire surface, isotropic properties, or directional properties. We found that textures to control the location of high and low strength are particularly useful (in Figures 9 and 10, the second image is the texture used to define the tensile strength property). To guide the crack to higher stress regions and to retrieve directional information from the texture, gradient operators are computed.

5 Rendering

Once the paths and widths of the cracks have been determined by the simulation, we pass this information to the rendering phase. It generates the peeling geometry on top of the original geometry, locally along the crack paths, and computes the final image with proper shading. The final rendering phase could be done with any high-quality renderer; we use Alias |Wavefront's Maya™.

After the crack is formed, new portions of the paint layer (sides and underneath the crack) get exposed to environmental attacks (*e.g.*, oxygen, UV light). The differential stress between the top and the bottom within the

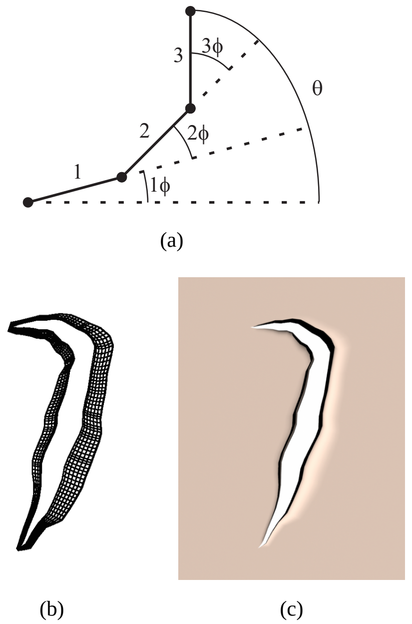


Figure 7: Geometry of the peels. (a) Cross-section of the curling geometry with three sections and angles $\theta = 90^o$, $\phi = 90^o/(1+2+3) = 15^o$. (b) Generated mesh. (c) Rendered result.

paint layer will cause this layer to curl. Instead of simulating this process in detail, we simply rely on a controllable approximation shown in Figure 7.

We compute the outward curling of the paint layer using a spiral-shaped geometry. The end of the curl forms an angle θ with the base surface (Figure 7(a)). This angle is user controlled and vanishes to zero at the end points of a crack.

To generate and render the effect of peeling, we create a mesh of micro-polygons with elements smaller than a user specified size (Figure 7(b)). A crack segment is subdivided in as many sub-segments as needed to respect this maximal size. It is also subdivided at each location where detail information is available (Section 4.6). Along the crack, the geometry is built generating one quadrilateral strip per sub-segment. To ensure smooth shading of the peels (Figure 7(c)), the surface normals of the micro-polygons are averaged and stored at every mesh vertex location.

This technique is simple and efficient, and can thus be generated on the fly in most standard rendering environments such as Maya™, or could be generated in a preprocess to create the peels geometry into a file added to the final scene. The approach has the advantage that the additional geometry is "glued" to the base surface, and thus does not require remeshing or modifying the objects. Some care must however be taken to add a small offset with respect to the original surface to avoid "surface acne" artifacts.

In the rendering process we also need to compute the shading of the base geometry. It must show the base layer color inside a crack and the paint color outside. This corresponds to evaluating if the point to be rendered is inside or outside a crack. We use a 2D grid structure to accelerate this test. We implemented this inside a plugin shader with user input for paint and base layer shaders and output of the appropriate color for the point being shaded. This is very flexible, allowing the use of any shader, 2D/3D texture, or other utilities to send the desired color to our shader. Shadows and other illumination effects are handled by the renderer.

	Door	Shutters	Wall
Simulation time†	75 min	20 min	3 min
Number of cracks	200	200	30
Number of segments	2900	1500	700
After merge	1200	850	250
Grid resolution	50 k	36 k	30 k
Rendering time‡	3 min	3 min	3 min
Number of polygons	400 k	150 k	130 k

Table 2: Statistics for the scenes of Figures 8, 9, and 10. † Simulations were computed on an Octane2 with a single MIPS R12k 400 MHz CPU. ‡ Rendering was done using the multiprocessing capabilities of Maya™ on an Onyx 3400 with 16 MIPS R12k 400 MHz CPUs.

6 Results

Figures 8, 9, and 10 present real photographs (left) and synthetic results (rightmost two) of our system for a garage door, wood shutters, and an indoor wall. When the peels are viewed from a closer viewpoint (right), the shading and shadowing clearly show how both the curl geometry and the base layer appearing inside the crack are important to the visual quality of the results. In Figures 9 and 10, the second image from the left shows the tensile break strength S_b texture used, with darker representing lower strength and lighter representing higher strength.

Table 2 summarizes the statistics for these three scenes. Our simulation system is time and memory efficient, requiring about 35 MB of memory for the presented simulations. The computation of the elastic relaxation is the most time consuming part (about 80% of the total simulation time). The synthetic images were rendered with high quality anti-aliasing at a resolution of 640×480 pixels.

7 Conclusion and Future Work

We have presented a simple, fast, and easy to use approach for crack generation and peeling on layers such as paint. If desired, the user may control the generation of cracks with textures to describe the different surface properties. The crack propagation is performed on the surface, with a 2D grid to query and update the various surface properties. As cracks propagate, they remove constraints in the paint layer, allowing it to slightly shrink. We simulate both this shrinking and the related loss of adhesion between the paint and the base layer. The result of the crack propagation simulation is passed to the rendering phase, which generates geometry to represent the curling process of peeling and uses the appropriate shader when inside or outside of the cracks. Our approach produces visually appealing results, which are close to observed phenomena.

In future work, we will treat pieces of peels which break off, as often happens in reality. To add further realism, we should be able to treat more than two layers, for example when paint is added over wallpaper, etc. Another important direction is the treatment of curved surfaces, which complicates both the crack propagation algorithm, in particular the determination of the directions of propagation, and the generation and rendering of curl geometry.

Finally, our overall goal is a complete system to treat a wide variety of deterioration effects, in an integrated and easy to control manner. This will require careful determination of parameter choices, which will undoubtedly be a combination of automatic and user-assisted solutions.

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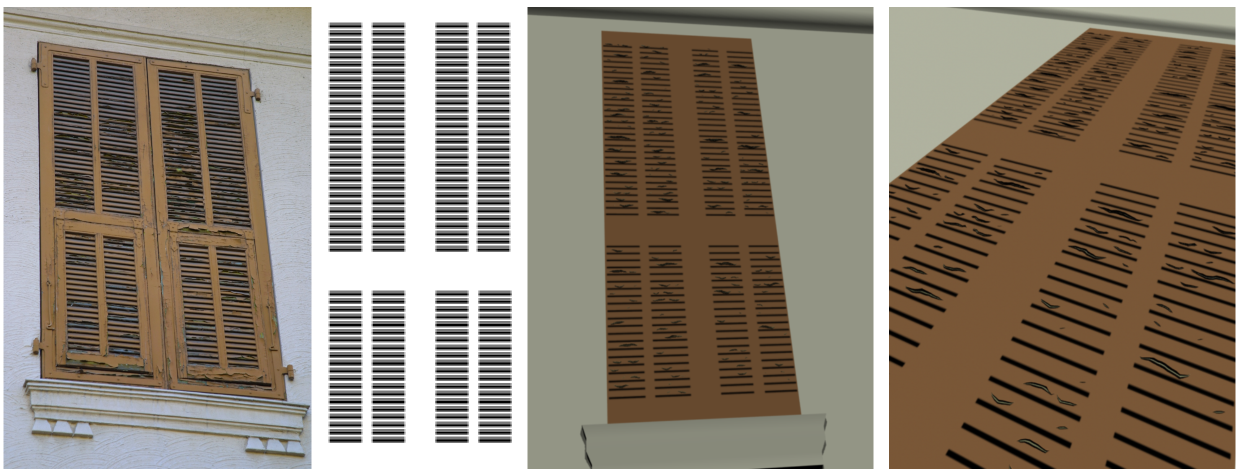
Real Synthetic Synthetic

Figure 8: Garage door with six wood panels having different crack properties.



Real Strength S_b Synthetic Synthetic

Figure 9: Wood shutters with peeling on the small lamina plates.

Real Strength S_b Synthetic Synthetic

Figure 10: Large peels over a painted plaster wall.