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Applying deflectometry techniques to non-reflective planar panels using add-on reflective material

Gary L. Rhoades and Micah Shepherd
Department of Acoustics, Pennsylvania State University Main Campus: The Pennsylvania State University - University Park Campus, Felton, PA, 17322; garyrhoades@comcast.net; mrs30@psu.edu

Jeff Harris
Pennsylvania State University Main Campus: The Pennsylvania State University - University Park Campus, State College, PA; jrh68@psu.edu

Reflected grid deflectometry is an optical method of vibration analysis relying on specular reflections to create amplifications of measured deformations in a planar test structure, resulting in high resolution slope and deflection plots of the test surface. Therefore, the structure under test is required to have a reflective surface. Application has so far been limited to ideal mirror-finished planar objects. An experiment is constructed to test the effectiveness of add-on reflective material on non-reflective planar panels for deflectometry measurements, using a collection of adhesive tapes, film, and spray. The structural deflection due to a point impact is measured, and results for each add-on material are then compared and discussed. The findings indicate that tapes, while cheap, are manufactured without strict tolerances on thickness, causing distortions in the reflected image and therefore the deflection plots. Film can be applied with limited success, but further testing is required to refine the application method. Spray-on reflective material, which is only applicable on transparent surfaces, produces deflection plots comparable in quality to those of an ideal mirror.

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1. INTRODUCTION

Deflectometry is a full-field optical method which can measure structural deformations with a high-speed camera. The reflected grid deflectometry technique has been well developed for the case of a reflective planar panel under excitation.[1] However, the reflected grid technique, which relies on specular reflections, would be much more useful if it could be applied to planar objects that do not have a naturally high level of reflectivity. A collection of reflective adhesive materials will be applied to rectangular plates to evaluate their effectiveness at creating specular reflections for deflectometry studies. The add-on reflective materials were specifically chosen to minimize impact on the structural vibration of the base structure and be relatively straightforward and versatile in their application. Given these characteristics, three add-on reflective materials were selected: adhesive tape, specialized film, and a spray-on paint.

The presented method of deflectometry relies on using a digital high-speed camera in-plane with a printed grid to take full field optical measurements of an entire object over discrete time increments. The reflected grid method used here depends on specular reflections to create amplifications of the measured deformations in the test panel. When either a static or dynamic load is applied to the panel, the panel will deflect and distortions will appear in the reflected grid images. Using basic geometric relationships, these distortions can be related to the deformation of the panel. These techniques have been refined over the last 70 years,[2–7] so the theory will only be briefly discussed here.

The alternating patterns created by the grid in both the x and y directions can be thought of as a phase pattern. When an excitation causes a shift in the line spacing, this creates a local phase variation $\Delta\phi$. There are already useful phase-shifting algorithms to extract the phase from the grid images.[8] In this work, the windowed discrete Fourier transform was used to convert grid images to phase plots. The phase-shifting algorithm will only give values between $\pm\pi$, with possible sharp discontinuities at the extreme values. Therefore, it is important to unwrap the phase to obtain a result with physical significance.[9]

After computing the fully unwrapped phase variations on the plate, $\Delta\phi$ can be mapped into slope fields. The reflected grid image from the panel will shift some distance δ after being excited. Simple geometric relations yield an expression for δ involving the distance L between the grid and test panel and the slope of the test panel. Another expression for δ can be written in terms of the grid separation pitch p, which can also be thought of as the spatial grid period, and the phase variation $\Delta\phi$. Equating the relations for δ directly maps the phase plots to slope fields. To obtain deflections, an inverse gradient is performed on the x and y slope fields, with the integration constant defined by setting displacement to zero for points on the panel prior to excitation. This process is explained in more detail in existing literature.[1]

2. ADD-ON MATERIAL TESTS

Two 12 x 18 x $\frac{3}{8}$ inch plates were used as the test panels for the evaluation. The first was acrylic with a mirror finish on one face, which was used to establish a reference case for the study. The second panel was a glass panel. A grid with 3.64 mm spacing was printed on paper and attached to a board which was situated between 21 and 36 inches from the plates, while a Phantom v1610 camera was used to record the images. The plates were supported on two sides by clamps and were impacted by an automatic force hammer (Scalable Automatic Modal [SAM] hammer by NV-Tech) at low amplitude. The setup is shown in Figure 1.

A. REFLECTIVE TAPE

Reflective tape is a widely available and cheap method to achieve a reflective surface on an object. Two reflective tapes were evaluated: Easy99 brand tape, made of 2 mil thick metallic mirror tape; and WOD brand tape, constructed from 1.5 mil thick metalized polyester. Both of these tapes were applied to the

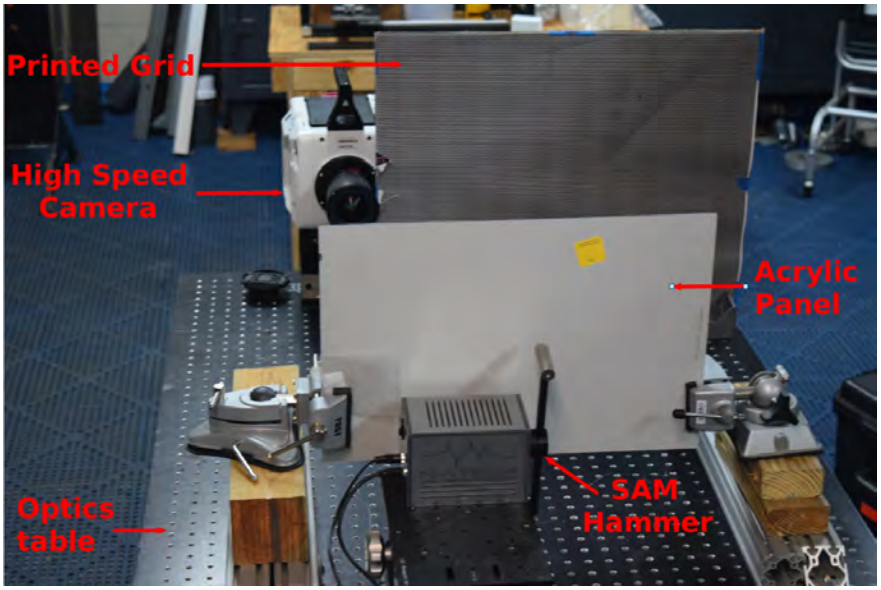
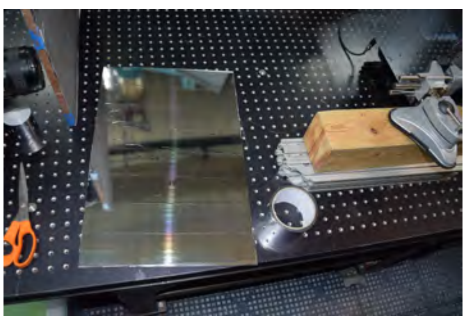
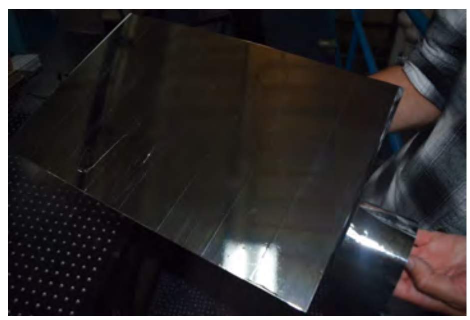


Figure 1: The setup for testing the acrylic panel. The camera is focused on the reflective side of the panel.

opaque back of the acrylic panel as well as a glass panel by carefully laying strips across the surface and smoothing them out with a dull plastic edge to remove as many air bubbles as possible. The overlapping lines of the tape act as slight deformities, which will be accounted for in the processing since the phase plot of a reference image is subtracted from each frame to obtain the local phase variation $\Delta\phi$. The total weight of each tape after application is unknown, which could have minor effects on the vibration of the panels.

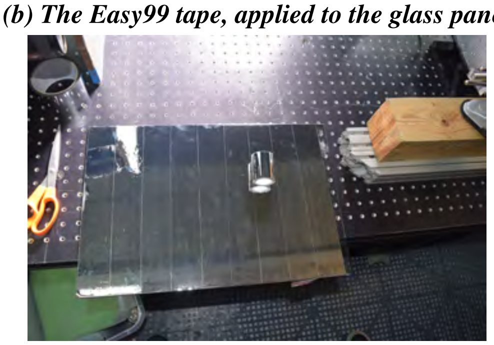


(a) The Easy99 tape, applied to the acrylic panel



(b) The Easy99 tape, applied to the glass panel

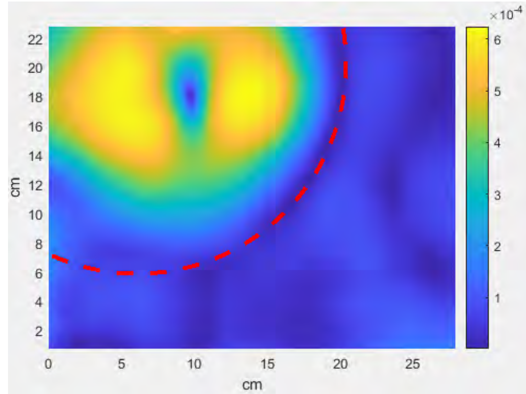
(c) The WOD tape, applied to the acrylic panel



(d) The WOD tape, applied to the glass panel

Figure 2: The metallic plastic tape and the metalized polyester tape are applied to both test panels.

(a) Raw data, L = 26.5"

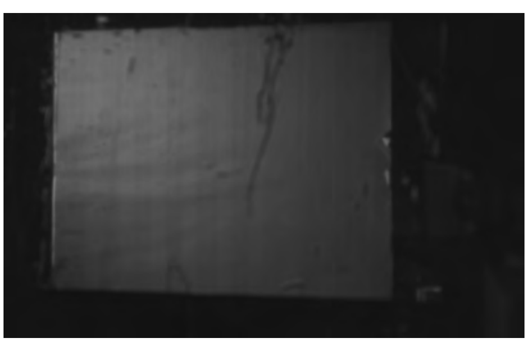


(b) A snapshot of the slope field 0.375 ms after impact.

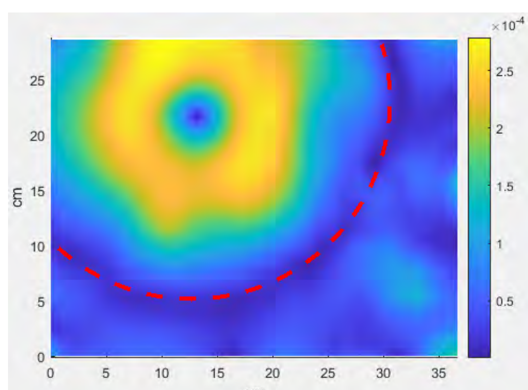
Figure 3: A raw image of the acrylic panel with the Easy99 tape applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.

The Easy99 tape took around an hour to fully apply to both panels. After using a dull plastic edge to smooth out the air bubbles as best as possible, the acrylic panel was mounted as before, with the tape side facing the camera. Some air bubble distortions could not be fully removed, but they did not seem to affect processing. However, this particular tape was not reflective enough to clearly see the grid lines in the reflection. The camera had a difficult time focusing, as the image appeared as mostly a single shade of grey where the distinct grid pattern should have been obvious. Figure 3a illustrates this in the raw image.

Despite the poor reflection, an impact was still visible in the slope field and a spreading wave was discernible. However, the wave was distorted and not symmetrical, as expected (see Figure 3b). The leading wavefront, seen as a dark blue circularly spreading line centered around the impact point, is irregular. A red dashed circle was placed above this leading wavefront to highlight any deviation from the perfectly circular spreading expected from such an impact. After the initial impact spreads out and combines with the reflections, it is hard to interpret the smaller slope values, as it appears more scattered and less accurate overall. These distortions are resultant from the lack of crispness in the grid reflection, and will be better quantified in Section 2.4. The Easy99 tape is not useful for high precision values of the slope field under small excitation and performed poorly on the acrylic panel.



(a) Raw data, L = 28.5"



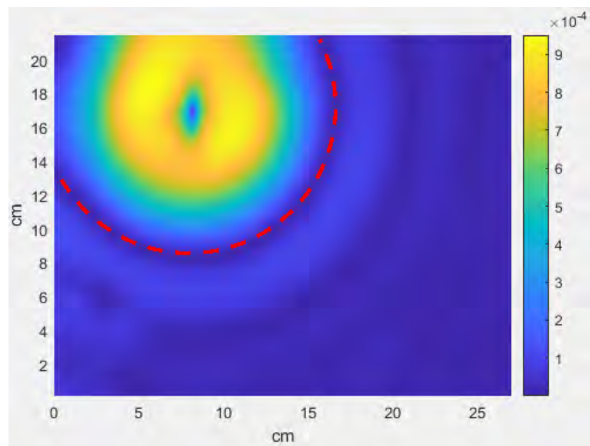
(b) A snapshot of the slope field 0.188 ms after impact.

Figure 4: A raw image of the glass panel with the Easy99 tape applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.

The glass panel provided marginally sharper images. Figure 4 shows the raw image and the respective slope field a few frames after impact. A shorter time elapsed after impact is shown for the glass panel because the wave speed is significantly higher in the glass than the acrylic. The grid has slightly better definition in the raw images, which in turn resulted in more symmetric spreading of the impact in the slope field. However, there is still a noticeable amount of distortion present in the circular spreading of the initial wave. Therefore, the application of the Easy99 tape for deflectometry of panels is not recommended.

The Easy99 tape was removed and replaced with the WOD tape option. Any bits of residue remaining after removing the Easy99 tape were easily cleaned with a damp towel. Once again, the process took around an hour, and a dull plastic edge was used to smooth out as many air bubbles as possible. As seen in Figure 5, the raw image of the acrylic panel is generally free of small defects, but upon closer inspection, the grid reflection is very wavy and warped. This would suggest many errors are introduced in the processed slope field, as the processing involves utilizing a fixed grid pitch to determine the phase plots. However, the test produced a slope field that is somewhat symmetric and regular after the impact. The WOD tape performed better than the Easy99 tape on the acrylic panel, but it still does not match the regularity of the mirror originally used. Therefore, the WOD tape applied to the acrylic would only be useful for seeing general slope patterns, without the need for high precision.

(a) Raw data, L ***= 22.5"***



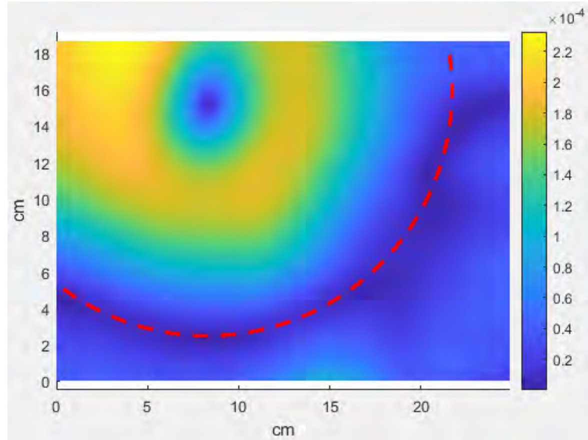
(b) A snapshot of the slope field 0.375 ms after impact.

Figure 5: A raw image of the acrylic panel with the WOD tape applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.

The glass panel was more troublesome with the new tape. The raw image in Figure 6 suffered from the lack of grid definition that was seen in the previous tape tests, and the slope field reflects this. The test gave a very distorted slope field compared to what would be expected of a propagating impulse along a flat surface. The WOD tape performed poorly on the glass panel, and would not be recommended for use in deflectometry experiments.

Upon closer inspection to both tapes, the thicknesses were not consistent. The tapes seemed to ripple when looking at them edge-wise. The manufacturers most likely have a larger tolerance of thickness than is required for achieving nearly perfectly flat adhesion to a surface. These ripples led to the undesirable distortions and poor focus of the camera on the grid. Therefore, the metallic mirror tape from Easy99 and the metalized polyester tape from WOD Tape are not well suited as an add-on reflective adhesive for deflectometry.

(a) Raw data, L ***= 21.5”***

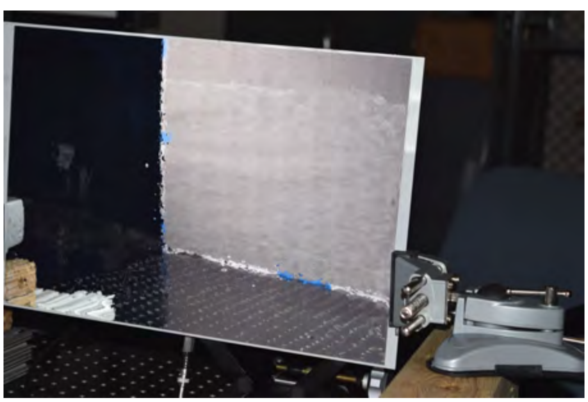


(b) A snapshot of the slope field 0.188 ms after impact.

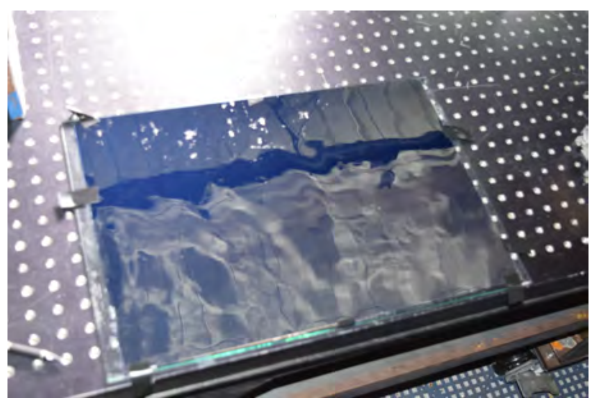
Figure 6: A raw image of the glass panel with the WOD tape applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.

B. REFLECTIVE FILM

A more expensive material was used to see if any advantage was clear over the cheaper tape options. Enhanced Specular Reflector (ESR) film from 3M was purchased in 26 by 26 inch pieces, rated to reflect greater than 98.5% of light. It has a thickness of 65 ± 4 microns, which is equivalent to about 2.5 mils. According to 3M, the ESR is an ultra-high reflectivity, mirror-like optical enhancement film, making it a perfect candidate for testing. The film was cut to fit the panels and adhered with consumer-grade roll-on adhesive. The mass of the film is low, with a value of 11.37 and 11.20 grams for the cutouts applied to the acrylic and glass panels, respectively. A dull plastic edge was once again used to smooth the film out.



(a) The ESR film, applied to the acrylic panel



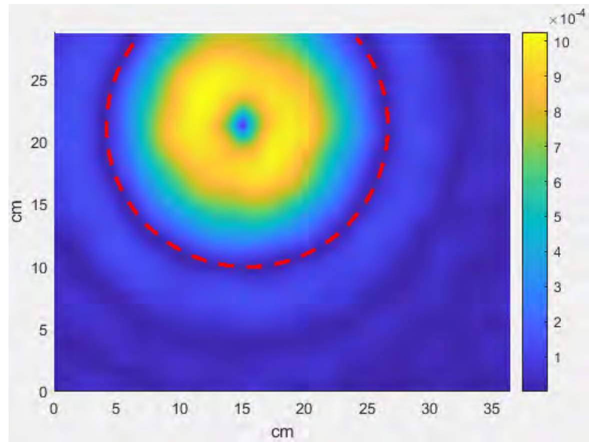
(b) The ESR film, applied to the glass panel

Figure 7: 3M ESR film, applied to both test panels.

The 3M ESR film is utilized in devices such as touchscreens for modern cellular phones, and is manufactured under tight tolerances. Upon inspection of the acrylic raw image in Figure 8, the grid is less distorted than in the images taken using the two previous tape options. However, the rows and columns of grid lines deviate horizontally and vertically over the length of the grid when the image is zoomed in. The application of 3M film on the acrylic panel achieved favorable slope field plots, with the impact wave nearly symmetrically spreading out. The impact is very well-defined with minimal noise infiltrating the slope field plots.

The grid lines, while not perfectly straight, only depart from their true direction within one or two pixel values. Since the grid-to-phase processing step relies on an established number of pixels per grid period, these disturbances likely result in the minor defects present in the slope field.

(a) Raw data, L = 27.6"

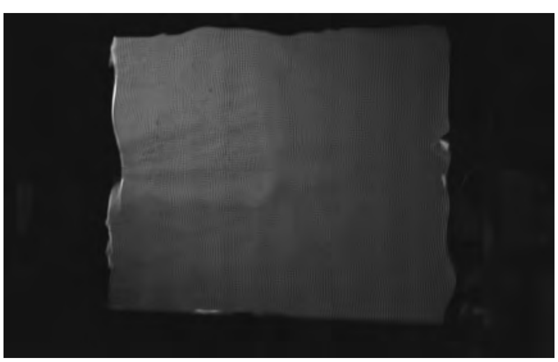


(b) A snapshot of the slope field 0.375 ms after impact.

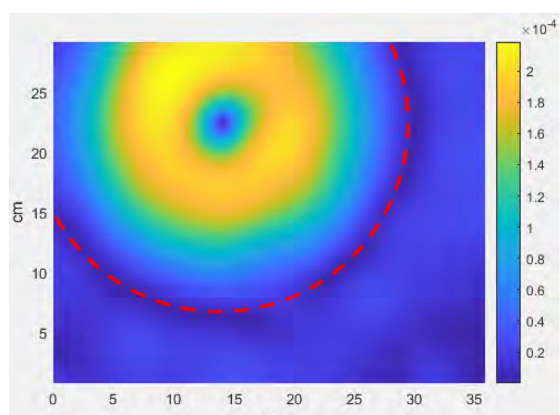
Figure 8: A raw image of the acrylic panel with the 3M film applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.

With the 3M film applied to the glass panel, the results are not as clean. Figure 9 shows the distortions in the raw image, especially noticeable along the left edge of the grid. Unfortunately, the 3M film did not form to the glass panel as well as the acrylic panel. The grid is overall very distorted and wavy, impacting the slope field which therefore appears slightly distorted. The general shape is preserved, but the details of the impact are not captured explicitly. The leading wave from the impact demonstrates this clearly, as there are several odd sections that deviate from the expected circular spreading.

Much care was taken when applying the 3M film to both panels, but it is certainly possible that the 3M film could have worked on the glass panel if it was attached more evenly. By naked eye, the adhesion looked promising, but attaching film to a surface might not be an ideal way to modify an object for deflectometry. It is too easy to create distortions in the raw images, leading to irregular or biased results.

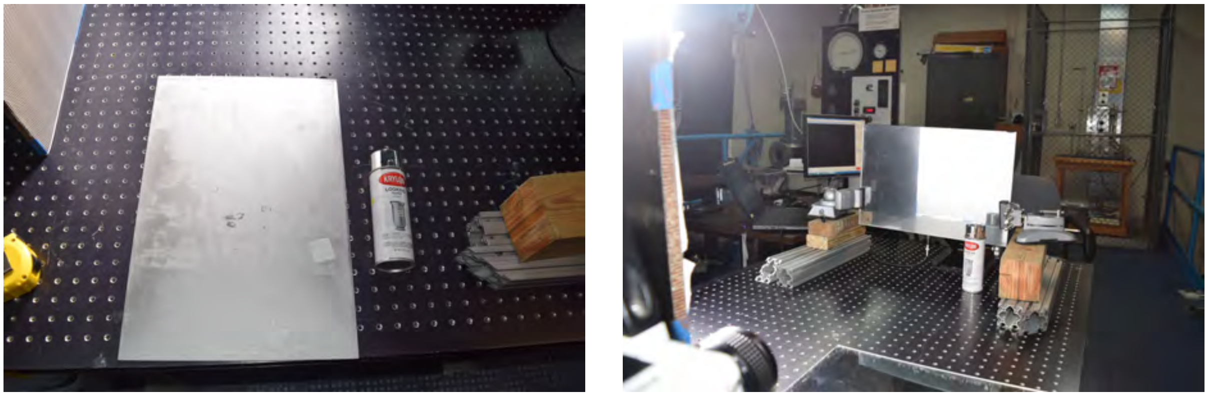


(a) Raw data, L = 30.0"



(b) A snapshot of the slope field 0.188 ms after impact.

Figure 9: A raw image of the glass panel with the 3M film applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.



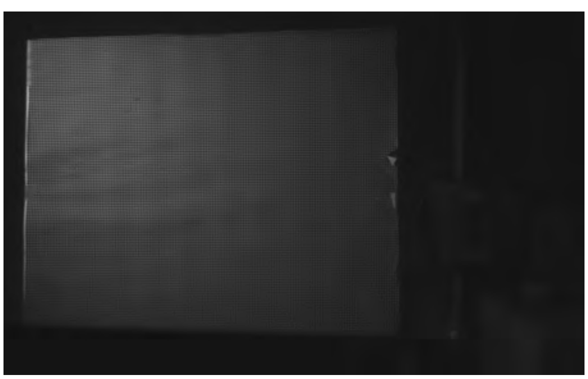
(a) The spray-on paint, applied to the acrylic panel *(b) The spray-on paint, applied to the glass panel*

Figure 10: Spray-on paint, applied to both test panels.

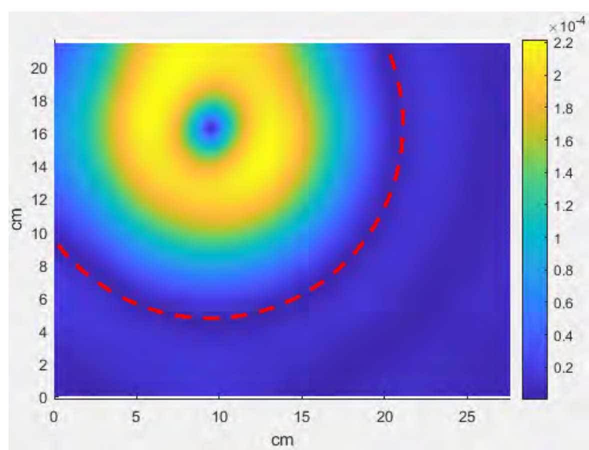
C. SPRAY

Finally, a spray-on reflective adhesive was applied to the glass test panel only. The spray is the Looking Glass silver spray by Krylon, meant to be used only on glass. The spray coats the surface, with the reflective side on the face of the glass, leaving a dull silver color on the side exposed to air. The reflective surface is therefore behind the material, similar to the mirror finished acrylic. Thus, the spray is only effective on the glass test panel, or other clear objects, and was useless on the acrylic test panel. Using many light coats of spray ensures even application across the surface. Therefore, 10 light coats were used, applied every minute, and then rested overnight. The spray can be easily removed after application onto a glass panel. The glass is both thin and distant enough from the camera that refraction effects are negligible.

The raw image in Figure 11 is as defined and crisp as any from an ideal mirror, and shows precise grid lines in the reflection. There is virtually no difference between the reflection of the grid in a perfect mirror and on the glass panel with the spray applied. The processed image came out nicely, as well. Unfortunately, there is no baseline for the glass panel to be compared to like the acrylic panel, but the clarity and symmetry of the impact in the slope field is as good as can be expected.



(a) Raw data, L = 28.3”

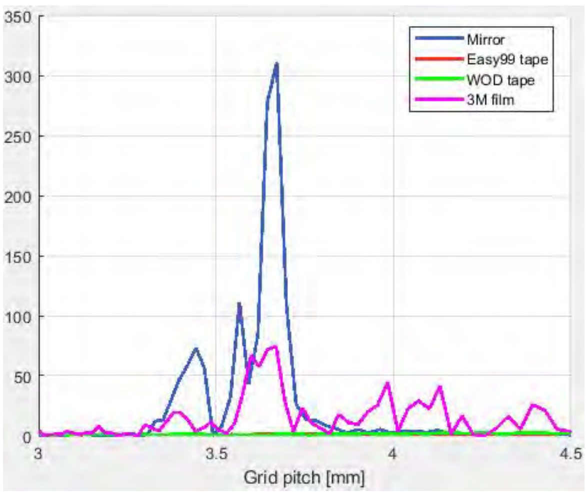


(b) A snapshot of the slope field 0.188 ms after impact.

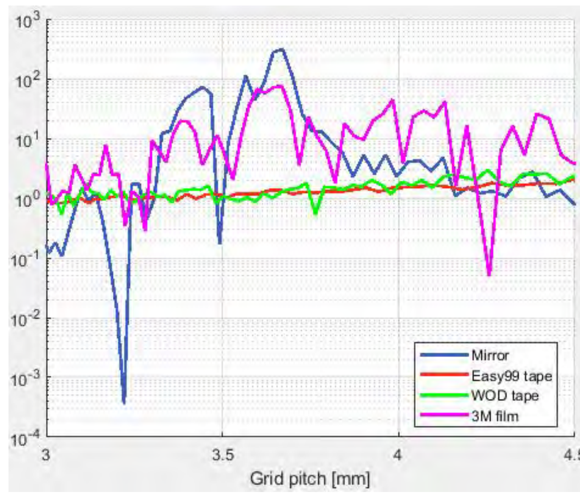
Figure 11: A raw image of the glass panel with the spray applied is shown on the left, while the processed slope field is shown on the right. The red circle indicates the wavefront with ideal spreading.

D. ANALYSIS

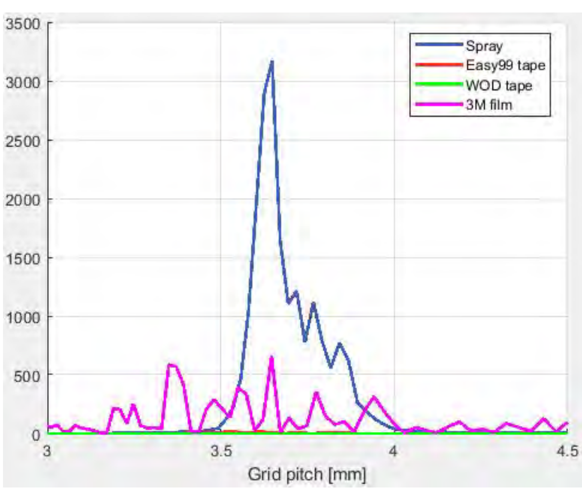
To better quantify how well each reflective add-on material performed, a selection of pixel rows from the raw images containing grid lines were transformed from intensity values to the wave number domain using a spatial Fourier transform. A distance increment equal to the ratio of meters per pixel was utilized to normalize each test. From here, the selected rows were averaged and turned into a power spectral density, with the value in each frequency bin representing a wave number. An inversion of this axis shows a peak centered around the calculated grid pitch value, which is exactly 3.64 mm. Because the crispness of the grid image determines the robustness of deflectometry, this process highlights the crispness or quality of the image.



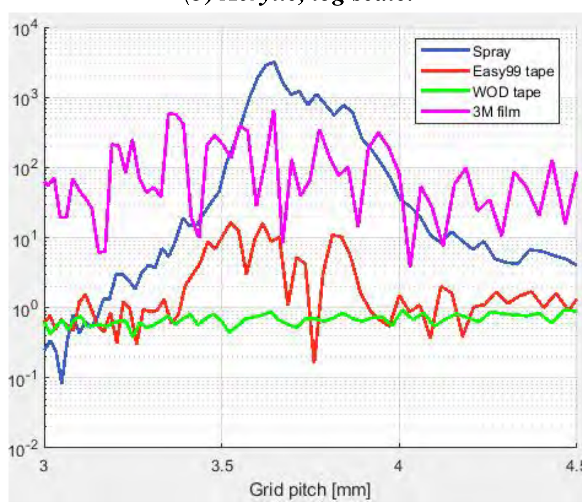
(a) Acrylic, linear scale.



(b) Acrylic, log scale.



(c) Glass, linear scale.



(d) Glass, log scale.

Figure 12: A comparison of the grid pitch calculation using each type of reflective add-on material. A logarithmic scale is additionally shown to highlight detail for the low amplitude tape cases.

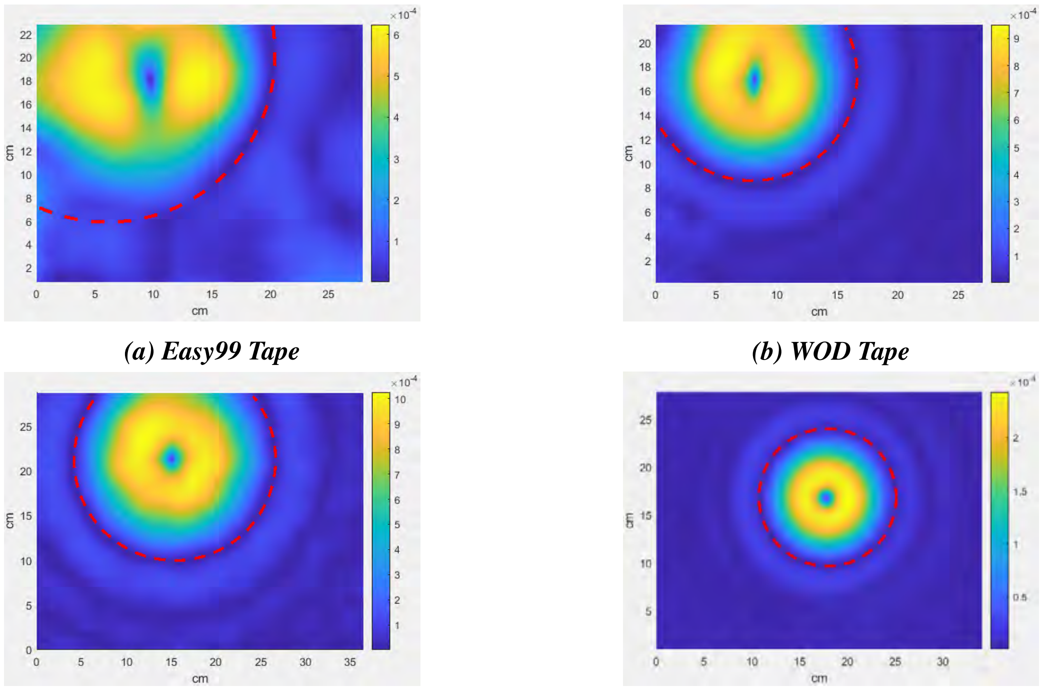
Figure 12 shows the comparison between each reflective add-on material for both the acrylic and glass panels. The logarithmic plot is included to better show behavior of the Easy99 and WOD tapes, which have very low amplitude compared to the 3M film, spray, and mirror finished acrylic. It should be known that the width of the peak is more important than an exact match with the defined grid pitch of 3.64 mm, as the magnification of the image was determined by counting the number of pixels that define the horizontal dimension of grid. For raw images with noticeable distortion, this count could be off by up to 50 pixels, which would shift the location of the peak while retaining the width. A wider peak implies less certainty, or definition, of the grid pitch. Therefore, a lower amplitude, wide, or poorly-defined peak represents poorer image quality than a sharp, large amplitude peak. Again, the x-axis was inverted to show grid pitch, in millimeters, instead of wave number.

The mirror finish for the acrylic panel has a very strong, narrow peak at 3.67 mm. This can be used as a baseline for all other tests, as it represents desirable image quality for deflectometry. The 3M film has a lower amplitude peak also centered at 3.67 mm, but is not as well defined. Several other strong peaks are present at higher values, indicating distortions in the image. Compared to the mirror finish, the 3M film agrees with the earlier conclusion of performing moderately well for deflectometry. While it isn't as crisp as the mirror finished acrylic, the images still produced nice slope fields with only a few distortions. Both the Easy99 and WOD tapes had nonexistent peaks when applied to the acrylic panel, once again reaffirming the previous recommendation of avoiding the use of these tapes in deflectometry measurements.

While the glass panel has no baseline, the spray-on reflective material produced a peak centered at 3.65 mm of similar prominence and width to the mirror finished acrylic, indicating great image quality and crispness. However, as observed in Section 2.2, the 3M film did not perform as well for the glass panel. There is a noticeable peak at 3.65 mm, but it is part of a wide series of peaks ranging from 3.25 mm to 4 mm. The correct peak is not significantly higher than the surrounding peaks, indicating the troubles with distortion and processing found earlier. The Easy99 tape is difficult to see in the linear plot, but the logarithmic plot exposes some features that indicate recognition of grid pitch in the correct region. However, the peak is very wide and flat, with values between 3.5 mm and 3.85 mm receiving almost equal weight. There are clearly enough distortions to classify the image quality as poor. The WOD tape again shows no signs of identifying the grid pitch. The calculation of the grid pitch for each add-on reflective material type agrees with observations of the processed slope fields.

3. CONCLUSION

Now that each reflective add-on material has been shown, a few conclusions can be made. The cheap reflective tape options, while the easiest to obtain, do not offer results that can be considered accurate, most likely due to manufacturing tolerances in thickness. However, a general visualization of the slope field can still be acquired. Next, the 3M film offered a decent look at the surface of the test object, with clearer images and better processed slope fields. Once again, there are still small distortions present and further testing should be performed to improve the application process. Lastly, the spray worked very well, but is limited in use on transparent surfaces, such as windows or clear plastics. A comparison of each add-on material for both panels is shown in Figures 13 and 14. Most importantly, the set of experiments shown here demonstrate that it is possible to apply an add-on reflective adhesive to a non-reflective planar surface and obtain a slope field using the method of deflectometry.



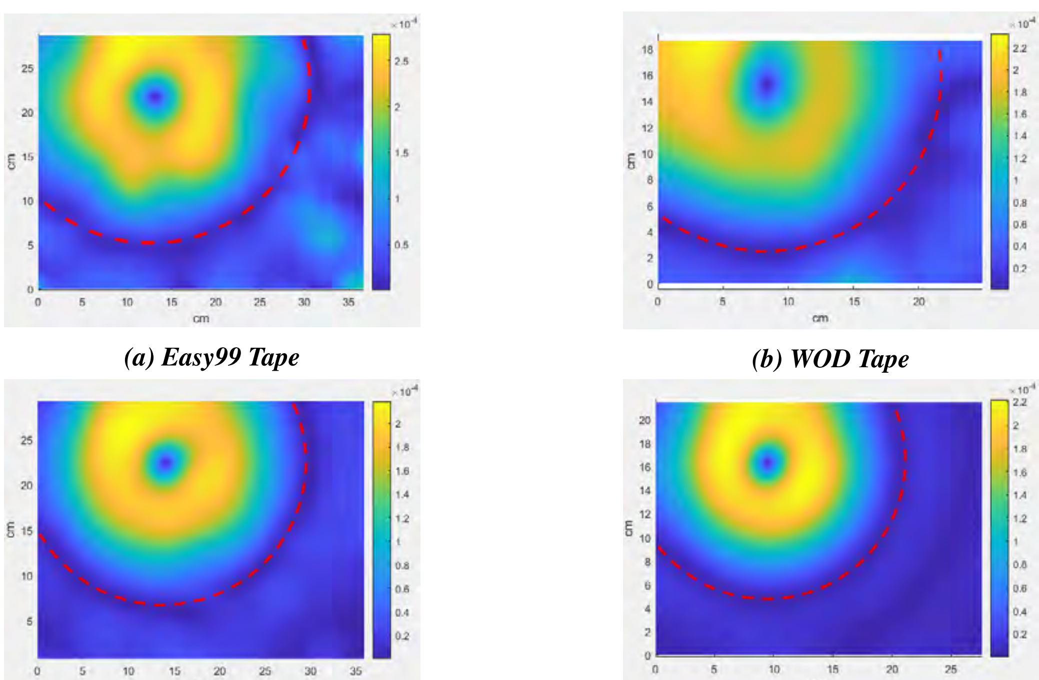
(a) Easy99 Tape

(b) WOD Tape

(c) 3M film

(d) Mirror finish (no add-on material)

Figure 13: A slope field comparison of each add-on material for the acrylic panel, as well as the original mirror finish without any added reflective material. All images are taken 0.375 ms after impact.



(a) Easy99 Tape

(b) WOD Tape

(c) 3M film

(d) Spray

Figure 14: A slope field comparison of each add-on material for the glass panel. The spray gave the best results, with the original two tapes coming out distorted. All images are taken 0.188 ms after impact.

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