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Benefits of Evaluating Interply Bitumen in Bituminous Roofing Membrane Samples in Assessments of Hail Impact Distress

Justin Donaldson, P.E., M. ASCE [1]
Marco DeLeon, M.E., P.E., M. ASCE[2]
Garrett Simpson, E.I.T.[3]

[1] Technical Director and Discovery Lab Director, Nelson Forensics, 2740 Dallas Parkway, Suite 220, Plano, Texas 75093; email: jdonaldson@nelsonforensics.com; phone: 877-850-8765

[2] Vice President – Special Projects, Nelson Forensics, 2740 Dallas Parkway, Suite 220, Plano, Texas 75093; email: mdeleon@nelsonforensics.com; phone: 877-850-8765

[3] c/o Nelson Forensics, 2740 Dallas Parkway, Suite 220, Plano, Texas 75093; email: info@nelsonforensics.com; phone: 877-850-8765

ABSTRACT

Hail impact evaluations of multi-ply bituminous roofing membranes such as built-up roofing (BUR) membranes, often include laboratory testing of field-procured membrane samples. Such testing is performed to further evaluate the samples for distress present within the membrane cross section. Popular tests performed by forensic laboratories in the United States include delamination, wherein a sample's individual plies are separated for observation with interply bitumen still present, and desaturation, wherein all bitumen is dissolved from a sample so the bare felt reinforcement mat can be directly evaluated. This paper addresses the potential shortcomings of using desaturation testing alone when evaluating roof membrane samples for hail impact distress, as distress or other conditions can be found in the bitumen that is not identifiable after the bitumen has dissolved. As the bitumen is the waterproofing element of the membrane, identification of bitumen damages and conditions is an important part of any evaluation that is missed from desaturation alone. This paper presents the findings from multiple roof membrane samples that were subjected to discrete impact forces, similar to hailstone impacts, and then examined by both delamination and desaturation. It is shown that distress to the bitumen may exist at impacted locations, without distress being identifiable on the reinforcing mats after desaturation. This testing is also supplemented with discussion of actual conditions found in delaminated membrane samples from actual hail-damage investigations. The potential for the mistaken identification of "false positives" for impact distress when evaluating desaturated felts is also discussed.

INTRODUCTION

BUR membranes are composed of alternating layers of asphalt-impregnated reinforcing felt plies and hot-mopped bitumen (typically asphalt, but sometimes coal tar). The felts themselves can be composed of organic fibers or inorganic fibers. The felt ply reinforcement provides dimensional stability and strength to the membrane, while the bituminous component provides waterproofing and adhesive properties.

Laboratory testing of BUR membrane samples can be an important part of a forensic evaluation aiming to determine if a roof has been damaged by hail impact. Such laboratory testing can confirm the presence of, or lack of, conditions consistent with an impact force within the layered membrane composition, providing information beyond what is obtainable during a field evaluation. The most common types of laboratory testing used for this purpose are delamination and desaturation.

There are distinct differences between these two types of tests. The authors of this paper have performed both types of tests and have reviewed similar laboratory work performed by others. Collectively, the authors have directly tested and evaluated over 2,000 BUR membrane samples through delamination and/or desaturation, in addition to similar testing that has been performed on polymer-modified bitumen membrane samples. This experience, in conjunction with reviews of the testing performed by others, has provided ample evidence of significant benefits to using delamination testing rather than desaturation. Such benefits are discussed herein. The basic process and characteristics of the two types of tests are described below.

Delamination Testing

Delamination of a BUR membrane sample consists of separating it into its individual plies, typically after freezing the sample. Using temperature manipulation to achieve delamination of a BUR membrane sample is briefly described in item 6.8 of ASTM D2829/D2829M – 07 (Reapproved 2019) "*Standard Practice for Sampling and Analysis of Existing Built-up Roof Systems*". While this item directly mentions dry ice as an aid for freezing the sample, samples are typically easiest to separate by hand after having been frozen with liquid nitrogen, in the authors' experience. After the plies have been delaminated, interply bitumen remains adhered to the topside and underside of each ply, allowing for direct visual evaluation of the bitumen. Additionally, the plies themselves can be visually and/or tactilely evaluated in this delaminated state.

Desaturation Testing

Desaturation of a BUR membrane sample is the process of dissolving all of the bitumen contained within the sample through use of a chemical solvent. The plies may or may not be delaminated prior to the desaturation, and often an entire sample is submerged at once in the solvent. The desaturating solvent is undiscerning and dissolves all of the bitumen in the sample, including both the mopped bitumen and bitumen impregnated into the felt plies themselves. This process leaves behind just the felt reinforcement fibers to be visually and/or tactilely evaluated. Solvent desaturation of a BUR membrane sample is briefly described in item 10.7.3 of ASTM D3746/D3746M – 85 (2015) "*Standard Test Method for Impact Resistance of Bituminous Roofing Systems*." This item mentions use of trichloroethane as the chemical solvent for asphalt-based membranes. While mainly considered an irritant, this chemical can cause acute toxicity with inhalation and emits toxic fumes when heated to decomposition, so care must be taken with its use. It is also known to destroy ozone in the upper atmosphere and is therefore considered harmful to public health and the environment (NCBI 2021). Other chemical solvents can be used to achieve desaturation however, including proprietary citrus-based cleaners, one of which is used in the authors' laboratory.

OBJECTIVE AND METHODOLOGY

An obvious benefit of laboratory delamination testing over desaturation testing, with regard to the identification of impact evidence in a given membrane sample, is that the former allows for evaluation of the bituminous component of a BUR membrane sample, whereas the latter does not (as the desaturation process destroys all of the bituminous component). Clear evidence of impact forces or other as-built conditions that may affect the waterproofing performance of the roof membrane can be readily observed in the bitumen. Furthermore, in the authors' experience, it has been apparent that evidence of an impact force can be found in the bitumen component of a BUR membrane sample more readily than in the felt ply reinforcement fibers. This hypothesis was tested experimentally in the laboratory, and the results are presented herein.

Broadly speaking, this experiment's methodology consisted of three phases. During the first phase, BUR membrane samples were impacted in a controlled manner with steel balls to impart kinetic energies at the point of impact that are comparable to hailstone strikes for a given hail size. During the second phase, the impacted samples were delaminated and evaluated. Finally, during the third phase, each sample's plies were desaturated and re-evaluated. The observed impact distress/evidence from both the delamination and desaturation evaluations was documented for each sample and compared to each other.

BUR Membrane Sample Acquisition

The membrane samples used for this experiment were cut from a roof system mock-up of approximately 100 square feet that was built by an experienced commercial roofing contractor. The mock-up was made in a controlled, warehouse setting and had never been subjected to actual hail activity. The mock-up roof system consisted of four inorganic plies (including the base sheet) set in asphalt moppings. The membrane was adhered to a 1" perlite substrate with hot asphalt. A flood coat of asphalt and gravel surfacing was applied to the top surface of the membrane.

The samples were cut from this mock-up, by the same contractor that built it, in a manner consistent with how field samples are typically obtained during forensic evaluations. The embedded gravel was removed along outlines of the samples by use of a spud bar, and the samples were then cut out along the spudded outlines with a powered reciprocating saw. Samples were cut approximately 16" x 16" in size to provide an approximate 12" x 12" central area that had not been disturbed during the spudding and cutting process.

Steel Ball Strikers

Steel ball drops can be used as a way of simulating hailstone impacts. Underwriters Laboratory (UL) Test Standard 2218 is an example of a test standard that utilizes steel ball drops. Consistent with UL-2218, four different sized steel ball projectiles were used in this experiment: 1.25" [31.8 mm], 1.50" [38.1 mm], 1.75" [44.5 mm], and 2.00" [50.8 mm] (**Figure 1**).

Dropping Apparatus

The BUR membrane samples were systematically impacted by the aforementioned steel balls. The balls individually impacted the samples by free falling from a targeting apparatus. This apparatus was similar to that described in ASTM D7052/D7052M - 17, "*Standard Test Method for Determining Impact Resistance of New Low Slope Roof Membranes Using Steel Balls*". The apparatus generally consisted of a tube affixed above, and perpendicular to, a test sample (**Figure 2**). The tube length was approximately 59". A pin in the tube allowed for a ball to be loaded into the top of the tube and then released in a controlled manner. For this experiment, two separate tubes were used: a 2.00" [50.8 mm] diameter smooth PVC pipe for dropping the two larger ball sizes and a 1.50" [38.1 mm] diameter smooth PVC pipe for dropping the two smaller ball sizes. The tubes could be lowered or raised along the apparatus frame to adjust the drop height for each different size of ball.

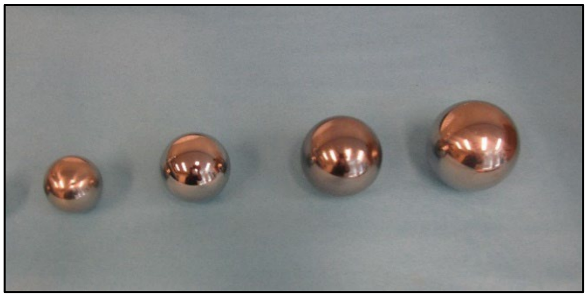

Figure 1: Steel balls used as impact strikers

Figure 2: Dropping apparatus, setup for a 20' [6.1 m] drop height

Sample Impact Parameters

Drop heights for the steel balls were taken from UL-2218, which are stated as being derived from the theoretical kinetic energies of actual hailstones of the same size. In other words, the drop height for a 1.50" [38.1 mm] diameter steel ball provides for a kinetic energy at impact that is similar to the theoretical kinetic energy of a 1.50" [38.1 mm] diameter hailstone falling at terminal velocity. While this allows for somewhat of a comparison between the impacts of the steel balls and hailstones, it is also important to keep in mind that steel and ice are different materials with different properties, which can affect the characteristics and distress resultant of impact. For example, unlike the steel balls, real hailstones can deform or crush during impact, affecting the transfer of kinetic energy. As such, the results from this paper should not be construed as being representative of hail-size damage thresholds for BUR membrane roofing, and determination of damage thresholds was not an intent or goal of this experiment.

The respective drop heights for the steel balls were 12' [3.7 m], 15' [4.6 m], 17' [5.2 m] and 20' [6.1 m], with respect to projectile size from smallest to largest. The associated theoretical kinetic energies of the drops are also provided in UL-2218. With these target kinetic energies and the measured masses of the actual steel balls used in the experiment, it was possible to calculate a target velocity at impact for each size of steel ball used. This data is summarized in **Table 1**.

Table 1: Steel Ball Measurements and Drop Parameters

Striker Ball Size		Striker Ball Mass		Drop Height*		Target Kinetic Energy*		Target Velocity at Impact	
(in)	(mm)	(slugs)	(grams)	(ft)	(m)	(ft-lbf)	(J)	(ft/sec)	(m/s)
1.25	31.8	0.00894	130	12	3.7	3.53	4.78	28.1	8.57
1.50	38.1	0.01545	225	15	4.6	7.35	9.95	30.8	9.40
1.75	44.5	0.02454	358	17	5.2	13.56	18.37	33.2	10.1
2.00	50.8	0.03664	535	20	6.1	23.71	32.12	36.0	11.0

**Sourced value from UL 2218*

"Calibration" checks were made with the actual experiment apparatus setups and steel balls by performing drops through a chronograph that measured the ball velocity to the nearest 1 ft/sec. These checks yielded velocities generally consistent with the target values.

Impacting Procedure

Six samples of BUR membrane were arbitrarily labeled as Sample A through Sample F. An approximate 1" long notch was cut near what would be designated as the "top right" corner of each sample, in order to maintain individual ply orientation after delamination. A clear plastic film template was also made for each sample, showing the notch location. A cross was painted onto the top surface of each sample to create quadrants, numbered as 1 through 4. Each quadrant received a single impact, and two different ball sizes were used to strike each sample. The impact schedule of the samples is summarized in **Table 2**. Each size of projectile was dropped a total of six times throughout the experiment, and each impact location was marked on both the top surface of the sample and on the sample template.

Table 2: Sample Impact Schedule

Sample	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4
A	1.50" [38.1 mm] Ball	1.50" [38.1 mm] Ball	1.25" [31.8 mm] Ball	1.25" [31.8 mm] Ball
B				
C				
D	2.00" [50.8 mm] Ball	2.00" [50.8 mm] Ball	1.75" [44.5 mm] Ball	1.75" [44.5 mm] Ball
E				
F				

Evaluation Procedure

Samples were delaminated after the impacting procedure was completed. Delamination was performed by freezing the sample with liquid nitrogen and then separating the plies by hand. The delaminated samples were then evaluated. The evaluations were made with visual and tactile assessment techniques (e.g., focused lighting, light bending of the plies, application of finger pressure). Evidence of impact distress was documented, and all plies were photographed. After this evaluation, the samples were desaturated. Desaturation was performed by allowing the separated plies to soak in a room-temperature, citrus-based cleaning solvent. After soaking, the plies were washed with clean water and allowed to dry. The desaturated plies were then re-evaluated using visual and tactile assessment techniques. Evidence of impact distress was documented, and all plies were photographed again. Both evaluations were aided by use of the sample template that outlined the impact locations.

RESULTS AND DISCUSSION

Delamination Observations

Delamination of the samples revealed disturbed interply bitumen at most of the impacted locations. These disturbances appeared as circular areas of rippled bitumen, and are similar to disturbances that the authors have routinely encountered in laboratory samples that were evaluated in conjunction with actual hail-damage investigations (**Figure 3** and **Figure 4**). The centers of the disturbances aligned with the impact points, with the rippling radiating outward from the impact point. The likelihood of a bitumen disturbance being present, and the sizes of such disturbances, increased with increasing projectile sizes.

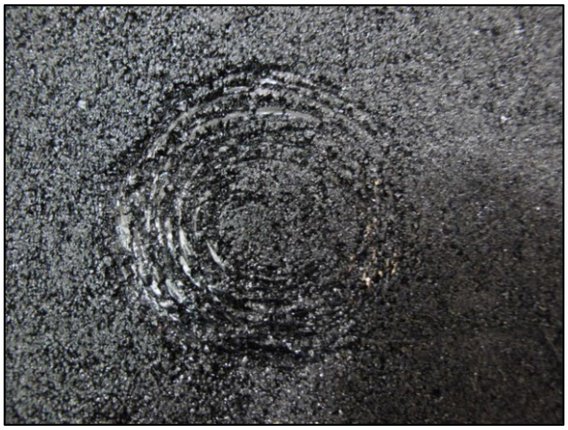

Figure 3: Impact disturbance to interply bitumen from impact E-3

Figure 4: Impact disturbance to interply bitumen from a roofing membrane found to be damaged by actual hail

It was noted that the extended disturbance rings around the impact point did not appear to be the result of direct crushing by the projectile itself. Rather, the pattern is akin to a lateral "shockwave" propagation, similar to the surface of a pond after a rock has been dropped/thrown into it. The rippling pattern indicates a lateral dispersion of the impact energy through the bituminous medium. With actual hailstones that might crush or deform during impact, such energy dispersion may be less intense and result in a more subtle disturbance pattern. Damage evaluations from actual hail-damage investigations support this theory, as observed bitumen disturbances are often more subtle than those observed to have been caused by the steel balls in this experiment. However, the bitumen disturbance patterns resulting from either steel balls or hail are similar.

The authors also observed that ply ruptures were evident at several of the impacts (**Figure 5** and **Figure 7**). Similar to the bitumen disturbances, the likelihood of a ply rupture being present, and the sizes of such ruptures, increased with increasing steel ball sizes. In all cases where a ply rupture occurred, a bitumen disturbance was also present; however, not all bitumen disturbances coincided with a ply rupture. The ply ruptures occurred as linear, arc-shaped, or multi-legged fractures and extended through, or immediately adjacent to, the center of the impact disturbances. In no situation did an impact cause a distinct oblong or circular hole through a felt ply. While the ply ruptures were typically evident from visual evaluation alone, application of light pressure at the rupture made them more visible and easier to photograph (**Figure 7**).

To the authors' knowledge, the long-term effects that bitumen disturbances (from impact) have on the waterproofing performance and/or service life of a membrane have not been fully researched and are not specifically known. Research regarding the long-term effects of bitumen disturbances is beyond the scope of this paper, and an assumption that the presence of disturbed/rippled bitumen compromises a BUR membrane would be a conservative approach to distress evaluation in the absence of data to indicate otherwise. However, without a rupture through its full cross section, a membrane with disturbed bitumen may continue to provide adequate waterproofing, at least in the short-term and possibly longer.

Desaturation Observations

After desaturation, no bitumen disturbances could be identified as the bitumen component had been dissolved and removed from the plies. Additionally, there were no corresponding disturbances of the felt plies that specifically mimicked the locations/extents of the previously observed bitumen disturbances (i.e., there was no evident transmission or translation of the full bitumen disturbance to the felt ply reinforcement). Felt ply ruptures were observed at several of the impacts. However, for every impact that resulted in felt ply ruptures, the ruptures were first observed while the membrane was in its delaminated state, meaning desaturation was not necessary to find that ruptures had occurred.

Observation Summary

Data from the evaluations of each impact location on the tested samples is summarized in **Table 3** through **Table 6**. These tables indicate the frequency at which interply bitumen disturbances and ply ruptures were observed for each impact. The entries appear as fractions where the denominator indicates the total number of material layers (either interply bitumen layers or plies) that exist at the respective impact location, and the numerator indicates the number of those material layers that exhibited the respective condition (i.e., bitumen disturbance or ply rupture). For example, an entry of "3 / 4" in the middle column of a table indicates that three of four interply bitumen layers exhibited a bitumen disturbance at that impact location. A numerator value of "-" in the table means zero. The number of bitumen layers is always one less than the number of plies, as the an interply bitumen layer is defined as the layer of bitumen between two plies. Some impact locations list a higher number of total plies and bitumen layers than others because these impacts occurred over a ply overlap/seam within the sample.

Table 3: Observation Summary for 1.25" [31.8 mm] Steel Ball Impacts

Impact ID	Bitumen Layers with Disturbance	Plies Ruptured
A-3	- / 3	- / 4

A-4	1 / 3	- / 4
B-3	3 / 3	- / 4
B-4	- / 3	- / 4
C-3	3 / 3	- / 4
C-4	2 / 4	- / 5

"-" signifies a result of zero

Table 5: Observation Summary for 1.75" [44.5 mm] Steel Ball Impacts

Impact ID	Bitumen Layers with Disturbance	Plies Ruptured
D-3	4 / 4	- / 5
D-4	3 / 3	- / 4
E-3	3 / 3	- / 4
E-4	3 / 3	2 / 4
F-3	3 / 3	3 / 4
F-4	3 / 3	- / 4

"-" signifies a result of zero

Table 4: Observation Summary for 1.50" [38.1 mm] Steel Ball Impacts

Impact ID	Bitumen Layers with Disturbance	Plies Ruptured
A-1	- / 3	- / 4
A-2	1 / 3	- / 4
B-1	3 / 4	- / 5
B-2	4 / 4	1 / 5
C-1	2 / 4	- / 5
C-2	4 / 4	- / 5

"-" signifies a result of zero

Table 6: Observation Summary for 2.00" [50.8 mm] Steel Ball Impacts

Impact ID	Bitumen Layers with Disturbance	Plies Ruptured
D-1	4 / 4	4 / 5
D-2	3 / 3	3 / 4
E-1	3 / 3	4 / 4
E-2	3 / 3	4 / 4
F-1	3 / 3	3 / 4
F-2	3 / 3	4 / 4

"-" signifies a result of zero

The data from the Tables 3 through 6 are further summarized in **Table 7**, which indicates the four different possible combinations in which bitumen disturbances and felt ply ruptures could have been observed/absent at each impact. As indicated in the table, some of the impacts from this experiment resulted in a bitumen disturbance without a corresponding felt ply rupture. However, there were no cases where impacts caused felt ply ruptures but not an interply bitumen disturbance.

Table 7: Summary of Observation Combinations for All Impacts

	# of Samples with Condition of Having:			
Steel Ball Size	No Bitumen Disturbance & No Felt Ply Rupture	Bitumen Disturbance, but No Felt Ply Rupture	Bitumen Disturbance & Felt Ply Rupture	Felt Ply Rupture, but No Bitumen Disturbance
1.25" [31.8 mm]	2	4	-	-
1.50" [38.1 mm]	1	4	1	-
1.75" [44.5 mm]	-	4	2	-
2.00" [50.8 mm]	-	-	6	-

"-" signifies a result of zero

Differences in Evaluation Techniques

The impact disturbances to the interply bitumen were visually distinctive, which is generally consistent with the authors' experiences with samples evaluated as part of actual hail-damage investigations. This allows for a straight-forward visual evaluation of the sample. The distinct visual evidence in the bitumen also focused the evaluator's attention to the specific impact location on the plies, where targeted supplementary tactile evaluation could then be used. In contrast, the evaluation of the desaturated felts proved to be a more difficult visual task. While in the delaminated state, ply ruptures contrasted with the immediately surrounding bitumen, providing a visual clue of their presence. However, this contrast was lost form desaturation, making strict visual identification of the ruptures more difficult after desaturation (**Figure 5** and **Figure 6**). The loss of visual cues in the bitumen also necessitated a more tactile approach to evaluation of the desaturated felts, which was more tedious than the straight-forward visual evaluation of the delaminated plies. In either state, application of light tactile pressure at a rupture made it easier to identify and photograph (**Figure 7** and **Figure 8**).

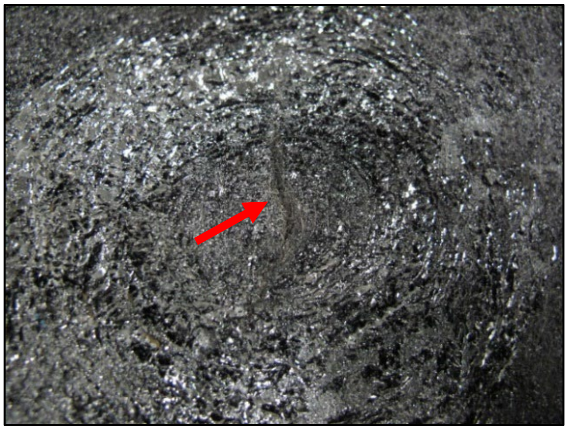

Figure 5: Interply bitumen disturbance with felt ply rupture evident (annotated), from impact D-1

Figure 6: Same felt ply and location as shown in Figure 5, after desaturation

Figure 7: Interply bitumen disturbance with felt ply rupture evident, from impact F-2 (light pressure applied from below)

Figure 8: Same felt ply and location as shown in Figure 7, after desaturation (light pressure applied from below)

Conditions That May Be Missed from Desaturation Testing Alone

Impact disturbances are not the only bitumen conditions lost during desaturation testing, as-built conditions within the bitumen are lost as well. This can result in improper identification of felt ply distress. For example, large as-built mopping voids may exist. Previous research has indicated that mopping voids can result in the development of localized membrane surface distress that may be mistaken for hail-impact damage (Donaldson, et.al 2015). Other evidence lost during desaturation can include small debris items (e.g., rocks) that were trapped between membrane plies during installation. The authors have encountered both voids and trapped debris in numerous samples from actual hail-damage investigations. In cases of trapped debris, the debris can be plainly seen in a delaminated state but may fall out of the sample during desaturation when it disengages from the dissolved bitumen that had previously encased it. If an entrapped piece of debris had damaged a felt ply due to its mere presence, then that damage would be seen after desaturation without the full context of the actual cause (**Figure 10** and **Figure 11**).

Figure 10: Small rock trapped between a sample's membrane plies, from an actual hail-damage investigation

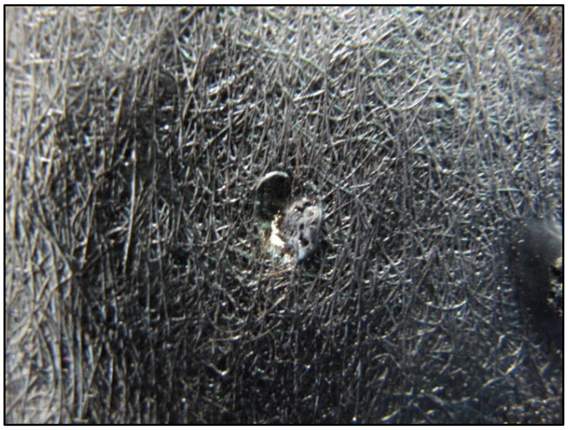

Figure 11: Adjacent felt ply indented and ruptured from the entrapped rock shown in Figure 10 (not consistent with impact)

Microscopic Damage to Felt Plies

In the authors' experience, some may argue that very small or microscopic felt ply ruptures can only be found after desaturation. However, on a sufficiently magnified or microscopic level, felt reinforcing plies will be observed to include minute discontinuities, inherent from manufacturing, consisting of individual fiber strand ends and gaps/voids between individual fibers. Thus, isolated, very small or microscopic discontinuities of the ply reinforcement do not deviate in any significant manner from the manufactured condition of typical felt reinforcement. Furthermore, it cannot be made clear that any very small or microscopic discontinuities in a reinforcing ply are actual evidence of a sustained impact, rather than an arbitrary manufacturing defect or damage incurred from some other cause. As noted in this paper, interply bitumen disturbances serve as the most consistent and reliable evidence of a potentially damaging discrete impact force having been sustained. In the authors' experiences, microscopic evaluations of desaturated felts can be misinterpreted as evidence of impact damage, or can potentially be abused to misrepresent innocuous or innate conditions.

CONCLUSIONS

The experiment described in this paper was designed to test a hypothesis that evidence of an impact force can be found in the bitumen component of a BUR membrane sample via delamination, even when there is no physical damage evident to the felt ply reinforcement fibers after desaturation. The experiment confirmed this hypothesis. From this experiment, it is clear that evaluation of the membrane bitumen, via delamination testing, is beneficial to a hail-damage investigation and that evaluation using desaturation testing alone will exclude valuable data found in the bitumen. Additionally, the evaluation processes showed an added benefit of delamination testing over desaturation, in that the delamination evaluation was more visual and straight-forward, while still allowing for identification of felt ply ruptures caused by impact. In fact, during this experiment, for every impact that resulted in felt ply ruptures, the ruptures were first observed while the membrane was in its delaminated state, meaning desaturation was not necessary to find that ruptures had occurred. Furthermore, the authors' previous experiences have indicated other significant conditions/evidence identifiable in interply bitumen, such as mopping voids and entrapped debris, that will be missed if delamination is not performed. This could result in misrepresentation of the actual causation of felt ply damages or other distress at a roof membrane.

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