Journal of the

National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org

ISSN: 2379-3252

DOI: 10.51501/jotnafe.v40i1

Vol. 40 No. 1 June 2023

Forensic Analysis of Roof Deterioration Due to Condensation

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Abstract

Corrosion of the structural steel roof deck of large warehouses resulted in several invasive forensic investigations to determine the cause and mechanism of the corrosion. The warehouse roof investigation presented in this paper is one of many similar warehouses located near the Gulf of Mexico and along the Southern Atlantic Seaboard experiencing corroded roof decks when constructed using fiberboard roof insulation made from sugarcane fiber called bagasse. Consensus exists among individuals studying this phenomenon that the fiberboard became saturated with water, which dissolved formic and acetic acid from the fiberboard. The steel deck corroded when it came in contact with the acidic solution. There was little consensus regarding the mechanism by which water intruded into the roof assembly. Invasive investigation of the low-slope roofs of buildings with various types of insulation (including bagasse fiberboard) and observation of physical commonalities between the instances led to the following conclusion: Water in the roof assemblies did not result from leaks through a compromised roof membrane but rather from humid air infiltrating the roof assembly and condensing on the underside of the roof membrane.

Keywords

Low-slope roof, condensation, roof membrane, structural roof deck, fiberboard, bagasse, acetic acid, formic acid, corrosion, wind load, Gulf of Mexico, Atlantic Seaboard, vapor barrier, destructive testing, humidity, roof leaks

Introduction

Although wood fiberboard insulation has been used for years as an inexpensive roof insulation, in the last several years, metal roof decks supporting low-sloped roofs (primarily located near the Gulf of Mexico and the South Atlantic Seaboard) began to fail due to corrosion. Investigating engineers agreed that the deck corroded when exposed to acidic solution of formic, and acetic acid dissolved from bagasse fiberboard insulation.

Bagasse is the fibrous material that remains after sugar is squeezed from sugar cane. Lacking is consensus about the mechanism by which moisture occurs in the roof assembly. The following case focuses on a forensic investigation in Texas near the Gulf of Mexico involving a low-sloped roof insulated with bagasse fiberboard where the corrosion of the metal deck occurred. The water intrusion was not unique to low-sloped roofs insulated with bagasse fiberboard; similar moisture conditions, without the severe corrosion, occur in roofs with other types of roofing insulation when exposed to similar environmental conditions.

Important consideration is given here to the characteristics of the fiberboard insulation itself, common environmental conditions, and the mechanism by which water saturated the insulation. This paper refers to these insulation boards made from wood pulp and bagasse collectively as "fiberboard." Reference to "roof assemblies" means the composition of insulation boards sandwiched between a roofing membrane and a structural deck.

Background

Since the early part of the 20th century, the construction industry has used panels called "fiberboard" made from wood fibers for various building components, including wall sheathing, cover boards (a thin substrate on the insulation to which the roof membrane is adhered), and roof insulation[1]. Fiberboard is produced through a wet process where the fibers are first washed, then the lignocellulosic fibers are combined with water and binders to create a slurry that is fed onto a moving screen to create sheets of various thicknesses whose fibers become interfelted as water leaves the boards[2]. The material is then heated to drive out the moisture and sometimes pressed or laminated

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before the panels are cut into boards[3].

In the early 21st century, the roofing industry became aware of premature roof deck corrosion on roofs insulated with fiberboard[4]. The corroded roof decks occurred in states bordering the southern Gulf Coast and southern Eastern Seaboard. Along with the similarity of construction (i.e., low-sloped roofs supported on metal deck), other investigators identified the common component in the failed roof assemblies as fiberboards made from "bagasse" fibers that remain after the sugar-manufacturing-process crushes sugarcanes to extract sugar[3].

Bagasse fiberboards have been produced since 1921 and used for roof insulation for 80 years as an inexpensive insulation material[3]. Although the insulation value of fiberboards insulation is relatively low (e.g., in the range of 3.0 per inch (in.) for fiberboard versus values exceeding 5.0 per in. for polyisocyanurate insulation), fiberboard insulation is appropriate for buildings such as warehouses that have minimal need for environmental control. One can visually differentiate fiberboard made using bagasse fibers from those made with wood fibers because bagasse fibers are slightly more course than wood fibers[4].

After earlier investigations associated bagasse with the corrosion of steel decks, controversies arose between investigators and the North American Fiberboard Association (NAFA) regarding the corrosive elements in bagasse fibers. The team of Chuck Marvin and Bruce Bryne proposed that fiberboard manufacturers poured liquid chlorine onto the unprocessed fibers to prevent mold[5]. The chlorine that remained in the fibers eventually leached onto the steel roof decks, causing corrosion. By contrast, Hopmann and Steiner opined that the findings of Marvin and Bryne did not account for the presence of other corrosive agents in fiberboard, such as carboxylic acid, acetic acid, and formic acid[6].

In March 2012, Mark S. Graham, executive director of the National Roofing Contractors Association (NRCA), published a paper expressing concern about this premature corrosion of steel decks. Graham stated that the corrosion of steel roof decks appears to be confined to roofs insulated with bagasse fiberboards[4]. In an undated publication, Louis Wagner, executive director of NAFA, denied that fiberboards were currently being manufactured with bagasse fibers[7]. That document states that the only manufacturer of bagasse fiberboards ceased production in 2006.

Typical roof construction affected by corrosion consists of a membrane roof (e.g., built-up bituminous, modified bituminous, or single-ply roofing) over a single, 1½-inch to 2-in. layer of fiberboard insulation mechanically attached or otherwise adhered to the structural steel deck. The economy of the fiberboard products over other insulation boards made this a popular insulation system for buildings such as warehouses and manufacturing plants where environmental control was less important. Eventually, however, in the early 21st century, awareness that roofs insulated with bagasse fiberboard were associated with corrosion of the structural steel decks eliminated bagasse fiberboards from use as a roof insulation board, although wood fiberboard insulation is still manufactured and readily available for use as wall sheathing.

In the subject case and similar cases, controversy remained over how moisture intruded into the bagasse-insulated roof assemblies. Intuitively, one expects that water leaks into the roof system when the roof membrane is breached, soaks the insulation, and then wets the steel deck.

The presence of multiple tears in the membrane led to one line of thinking that the fiberboard shrunk and tore the roof membrane. A second line of thinking concluded that the membrane failed because foot traffic caused joints over ribs (valleys in the deck profile) to deflect and collapse, ripping the roof membrane. The presence of linear tears with spacing that matched the dimensions of the fiberboard reinforced the foot-traffic explanation. Of the two explanations, the failure of the roof membrane at unsupported seams appeared more plausible. It is unlikely that the fiberboards shrunk and tore the roof membrane. Heat applied during the manufacturing process drives moisture out of the boards, causing them to shrink. Instead of shrinking, once installed, the fiberboards (as all wood products) absorb moisture from the air and expands. Adding to the controversy is the absence of similar corrosion failures in fiberboard-insulated roofs in northern states.

Location of Investigations

The subject investigation occurred in the southern region of Texas near the Gulf of Mexico. The description of corrosion in this study is similar to instances of corrosion of structural steel decks insulated with bagasse fiberboard that the NRCA reported in the southern and eastern coastal regions of the United States[4]. Buildings investigated in other matters involved warehouse facilities or warehouse portions of office/warehouse facilities that experienced partial or widespread deterioration of the structural decks within 10 years of construction. Due to the extent of loss to the buildings and the potential cost of remediation, the resulting litigation included multiple parties associated with the design and/or construction processes, each represented by an investigation team of architects, engineers, and attorneys. The investigations generated competing theories about causation.

Description of Case Study Site and Building

The subject of this investigation is a 360,000-square-foot warehouse located near Houston, Texas and the Gulf of Mexico. Its 900-foot-long axis is oriented in the east-west direction, and its 400-foot dimension is oriented in the north-south direction (**Figure 1**). Dock doors are located along the south and north faces of the building.

Construction of the building consists of concrete tilt wall exterior panels with a structural steel frame interior. A Type B steel roof deck rests on steel bar joists supported by the structural steel frame. The low-slope roof has a ¼-in.-per-foot pitch that drains from the ridge of the building (oriented in the east-west direction) down to gutters on the north and south edges of the roof. The roof assembly consisted of built-up bituminous asphalt roofing membrane on a single, 1½-in. layer of fiberboard insulation mechanically attached to the steel deck.

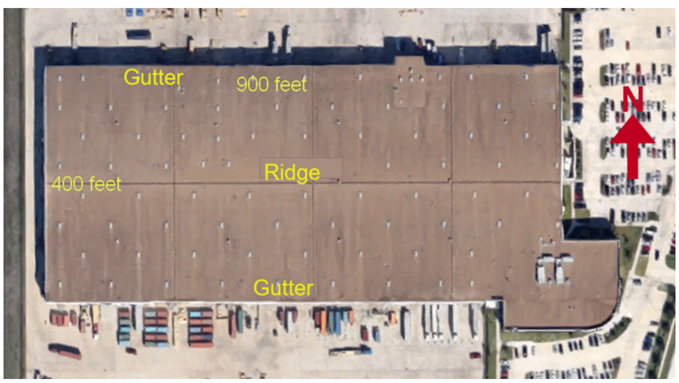

Figure 1
Aerial view of the subject warehouse.

Figure 2
Fractures in the roofing membrane running parallel to the south side of the warehouse. The arrow points to the south edge of the roof.

Within 10 years of original construction, the roof membrane of the warehouse began to fail. Splits formed in the roofing membrane with concentrations of deterioration near and parallel to the south and north sides of the roof (**Figure 2**).

Initial Hypotheses

Investigations of other warehouse facilities where the roofs deteriorated in the same manner as the subject roof preceded this investigation. Chemical analysis performed during those investigations established that the steel decks corroded when exposed to aqueous solutions containing acetic and formic acid. The design teams generally accepted this explanation of the cause of the corrosion. Disagreement remained about the source and mechanism of water intrusion.

Experts assigned to investigate this warehouse advanced different explanations about the sequence of events that introduced water into the roof assembly. Consistent with the theories of deterioration previously described in this matter, the hypotheses included the roof membrane splitting when the fiberboard shrinks after installation and foot traffic depressing the roof at unsupported joints in the insulation located over ribs in the steel deck. Either hypothesis would result in the roof membrane splitting and admitting rain water to enter the system. A third hypothesis proposed that condensation was the mechanism by which water collected in the roof assembly.

Site Investigation

To evaluate the substrate, contractors engaged by the plaintiff systematically removed areas as large as 4 feet (ft) by 8 ft (roof cores) in 31 locations. In performing each roof core, after the roof membrane was removed, the insulation was observed and then removed to expose the underlying steel deck. With the removal of each layer, experts observed, photographed, and sampled the materials. Observed conditions at most (but not all) roof cores included damage to the roofing membrane, corroded steel decks, and water saturated fiberboard (**Figure 3**).

During the investigation of the roof, the plaintiff's experts directed most of the invasive investigation focusing on areas where splits and repairs occurred in the roofing membrane. A request was made to conduct similar coring

Figure 3
Corrosion of the structural steel roof deck exposed by removal of roofing membrane and fiberboard insulation during destructive testing. Note standing liquid and prevalence of corrosion in the ribs of the steel deck.

Figure 4
Undamaged roofing membrane being removed. The long dimension of the roof membrane being removed is oriented north-south, and the view looks southwest across the roof.

Figure 5
Fiberboard insulation exposed after removal of the roof membrane seen in **Figure 4**. Note darker areas around the seams of the fiberboard insulation on the south end of the exposed roof that indicate the presence of moisture absorbed by the insulation.

where the roof membrane showed no evidence of damage (**Figure 4**).

Once the roof membrane was removed — exposing the insulation at the requested location where the roofing membrane showed no signs of deterioration — the insulation appeared wet (**Figure 5**). Removal of the fiberboard revealed that corrosion of the steel deck generally coincided with the joints in the insulation (**Figures 6** and **7**).

As shown in **Figures 6** and **7**, corrosion of the steel deck was pervasive, regardless of the condition of the overlying roof membrane. The roof investigation discovered that some insulation boards were installed with the joints between the fiberboard panels abutting over the ribs instead of resting on the flutes of the steel deck. This gave validity to the explanation that foot traffic

Figure 6
South end of the exposed roof deck. Corrosion of the structural steel deck beneath the fiberboard insulation layer seen in **Figure 4** and **5**. This shows corrosion coinciding with the seams in the insulation and confirms that corrosion can occur beneath undamaged roof membrane.

Figure 7
North end of the exposed roof deck. Corrosion of the structural steel deck beneath the fiberboard insulation layer seen in **Figure 4** and **5**. This illustrates that corrosion occurs beneath undamaged roof membrane and coincides with seams in the insulation. Corrosion is greatest in line with the damaged adjacent roofing seen in **Figure 4** and **5**. Areas of corroded and uncorroded decking suggest that although the moisture is pervasive across the plane of the roof, the insulation is not uniformly wetted.

may have deflected the unsupported ends of the boards and damaged the roof membrane (**Figure 8**). It was still unexplained, however, why more roof failures occurred near the edges of the north and south perimeter of the building, why the steel deck corroded beneath undamaged roof membrane, and why some steel deck was not corroded. Once the roof membrane fractures, water can penetrate the roof membrane through those fractures. However, the presence of corrosion where no roof membrane damage occurred suggests that water entered the

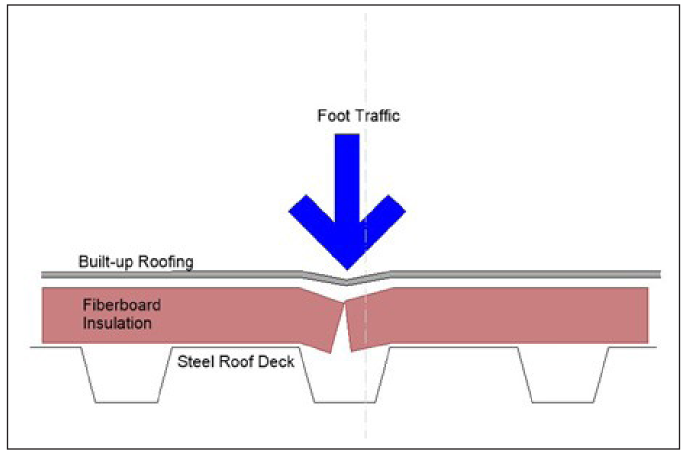

Figure 8
Illustration of the mechanism by which foot traffic damages unsupported joints that abut over the rib of the structural steel deck.

roof assembly by means other than through fractures in the roof membrane. The prevalence of distress at the north and south sides of the building indicates that the moisture intrusion is not necessarily uniform across the roof plane.

Chemical Analysis of the Fiberboard

Chemical analysis by laboratories engaged by the plaintiff verified the presence of acetic acid and formic acid in the fiberboard. In other similar cases, Hopmann and Steiner report elevated levels of chlorides, carboxylic acid, acetic acid, and formic acid in bagasse fiberboard[6]. Wood products naturally contain acetic and formic acid. Elevated temperatures, such as one finds in a roof assembly exposed to direct sun, accelerate the emission of volatile forms of acetic and formic acid in the wood,[8] lending credibility to this line of thinking. By contrast, in the manufacture of wood fiberboard, the washing process preceding placement of the wet slurry onto a screen is intended to remove most of the corrosive material[9].

The investigating teams were provided no documentation regarding the manufacturing process — specifically the washing of the fibers — of the bagasse fiberboard installed on the subject building. Since bagasse fiberboards were produced and used for years preceding the discovery of the corrosion resulting from their use, wood fibers used to make fiberboard also contain acetic and formic acid, and the corrosive fiberboard insulation appeared to be associated with one manufacturer, it was hypothesized that the corrosive materials in the bagasse may remain in high concentrations as a result of the manufacturing process used by the fiberboard manufacturer.

General Observations

In all buildings investigated, a single layer of bagasse fiberboard insulation was a common construction component. The reported prevalence of the moisture issue along the southern and eastern seaboards suggests that the deterioration of the steel deck, in all likelihood, relates to a combination of factors including the climate conditions, the bagasse material, and/or the roof assembly construction.

Climate Conditions

In all probability, finding corroded roof deck beneath undamaged roof membrane leads to the conclusion that moisture did not necessarily intrude through fractures in the roof membrane, but may have collected in the roof assembly due to condensation of water vapor in the roof assembly. This explanation is consistent with the technical memo issued by the NRCA concerning problems with fiberboard and with discussion in the NRCA Roofing Manual regarding condensation in roof assemblies where outside winter temperatures fall below 40°F, and the relative humidity of interior spaces exceeds 45 percent[10].

Climate conditions in southern coastal states are consistent with conditions noted by the NRCA that result in condensation forming in roof assemblies. Despite mild temperatures through the winter months in the southern coastal part of the country, it is not unusual for evening temperatures to drop below 40°F, combined with year-round humid conditions due to the proximity of southern coastal regions to large bodies of water, environmental conditions of temperature and humidity exist that result in condensation in roofing assemblies.

For example, in the Southern coastal region of the United States, during the winter daytime temperatures average 40°F to 50°F, and nighttime temperatures regularly drop to 30°F to 40°F[11]. Formation of condensation in this manner occurs due to seasonal or nightly drop in temperature[12]. Exposed to ambient temperatures, during the evening, the temperature of the roof membrane can fall below the dew point of air trapped in the roof assembly. February 11, 2010 represented typical noontime conditions during winter in the Houston. During the day when the interior of the warehouse is exposed to outdoor conditions due open dock doors, daytime temperatures were in the low 40s, the relative humidity was 93 percent, and the dewpoint temperature was 37°F to 39°F. At night, the ambient temperature fell to 37°F, below the dewpoint of air infiltrated from the exterior during the day. Not only is the roof membrane

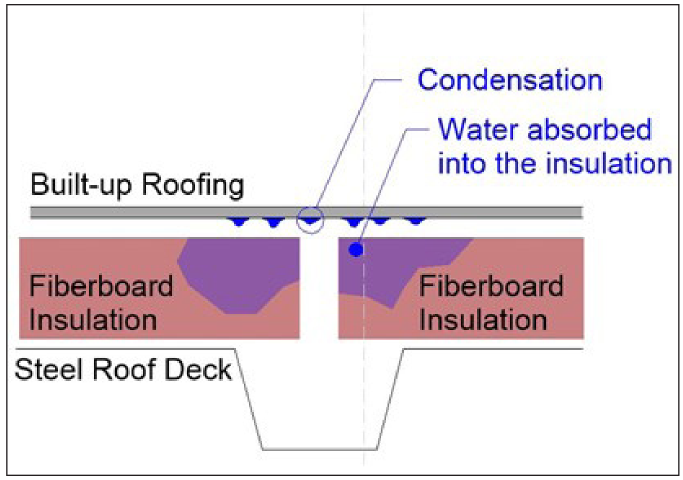

Figure 9
Illustration of the mechanism by which moist air condenses within the roof assembly.

cooled by the ambient temperature, but during the night, the surface of the roof also radiates heat to the sky. When this occurs, moist air trapped in the roof assembly that contacts underside of the cool roof membrane condenses (**Figure 9**).

Evaluation of climate conditions in the northern United States provides information that explains the lack of reports of corrosion on warehouses constructed similarly to warehouses in the southern coastal states. In summary, the climatic conditions in the north differ from those in southern coastal states — and do not encounter to the climatic conditions associate with corrosion of steel roof decks stated by the NRCA. Northern cities experience extended periods of nighttime temperatures below 40°F. Daytime temperatures are also low. However, even when the daytime relative humidities are high (because of the low temperatures), the capacity of the cold air to absorb moisture remains low. Even in the spring (when the climatic conditions might be expected to approximate those of wintertime in the Southern states), there is less difference between daytime and nighttime temperatures in Northern states. For example, a typical temperature range is illustrated by temperature and humidity at noon on March 31, 2010 in Chicago where the temperature was 72°F, but the relative humidity was 37°F. On that day, nighttime temperatures dropped only to the 60s — higher than the dewpoint temperature where condensation forms[13].

External and Internal Air Flow

The direct effects of air flow in buildings are caused by wind-induced pressures, stack-effect, and mechanical ventilation[14]. The operators of the subject warehouses typically close the doors of the facilities at night. In the case of the subject warehouse and other similar warehouses, the interior is heated during winter months. Experimentation and analysis by Stathopoulos, Surry, and Davenport found that internal pressures in buildings due to wind loads fluctuate significantly, varying the most near dominant openings in buildings and peaking when the wind direction is perpendicular to dominant openings[15].

The south-facing dock doors were used more frequently to manage product, exposing the interior of the warehouse to southerly Gulf winds. As the wind loads against the warehouse exterior vary, air pressure of the warehouse interior fluctuates (**Figure 10**). Aside from pressure due to wind forces, the stack-effect from rising warm air increases the interior air pressure slightly against the upper portion of the warehouse. Stacking-effects vary with the difference in temperature between the interior and exterior and with the increased elevation above the floor (i.e., at the rate of 0.2 Pascals per meter of building height or approximately 0.00001 psi per foot of building height)[16].

Consistent with the findings of Stathopoulos, Surry, and Davenport, the most severe roof damage to the subject building occurred along the south and north perimeters of the building where internal air pressures would be greatest. In addition, the storage racks located beyond the perimeter loading area block the flow of incoming air to the interior space[17], resulting in more infiltration of warm humid air and higher air pressures at the perimeter of the warehouse (**Figure 10**).

Migration of Air into the Roof Assembly

The Second Law of Thermodynamics states that matter and energy move from a higher potential to a lower potential and explains, in engineering terms, the mechanism by which air from the interior of the building moves into the roof assembly and how moisture moves within the roof assembly. Air moves from higher pressure to lower pressure, non-gaseous material moves from higher elevation to lower elevation, and moisture migrates from wet to dry. By this means, air from the interior of the warehouse is either pushed into, or pulled from, the roof assembly, and liquid from condensation drains to the ribs of the steel deck.

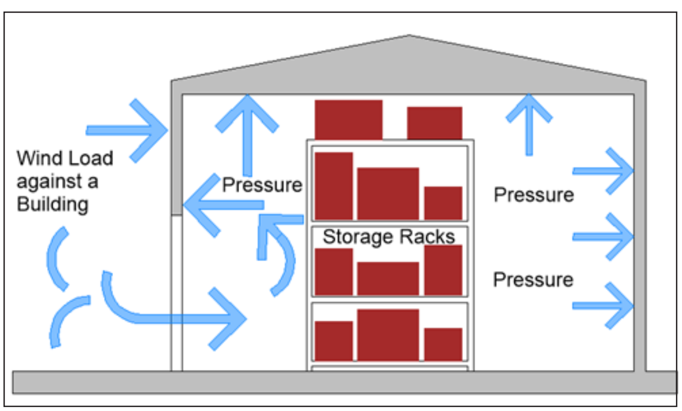

Figure 10
Wind-induced pressure in the building due to wind load on one face resulting in higher air pressure at the perimeter of the building next to the opening through which the wind enters the building.

The interstitial space between the steel roof deck and the roof membrane has a series of voids created by the ribs of the steel deck and joints between the fiberboard panels[18]. The pathway for air to migrate from the warehouse into the roof assembly is through the laps and other openings in the steel deck (**Figure 11**). As air pressure fluctuates, air migrates into and out of the roof assembly from the warehouse through the openings in the steel deck. Air is pushed into the interstitial space of the roof assembly as air pressure in the warehouse increases and leaves the interstitial space as the air pressure in the warehouse decreases. On buildings covered with a mechanically attached single-ply membrane roof, the membrane will lift as wind blows across the roof surface, creating negative pressure in the interstitial space of the roof assembly. This acts as a bellow and pulls air into the interstitial roof space (**Figure 12**).

The air below the steel roof deck has elevated humidity since the rising warm air absorbs and carries moisture with it[19]. Once inside the roof assembly, this humid air can move through voids in the ribs of the deck and through the seams in the insulation until it reaches the underside of the roof membrane. If the surface of the roof membrane is at or below the dew point, condensation occurs, and the

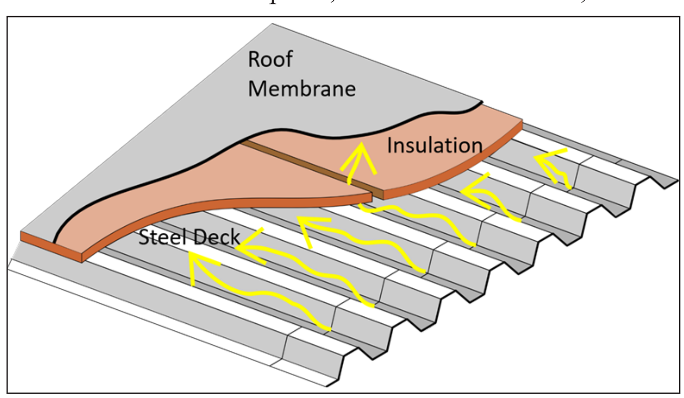

Figure 11
Illustration of the path of air infiltrating the structural steel deck and the fiberboard insulation.

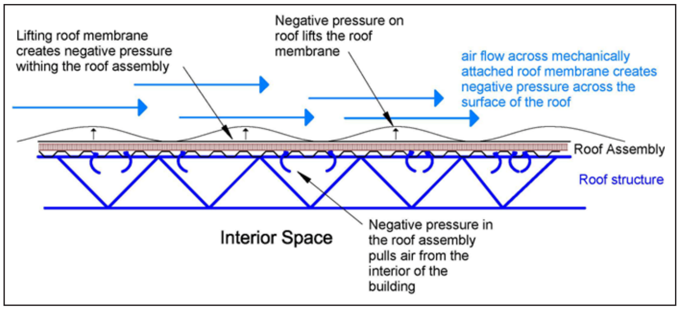

Figure 12
Wind across the roof surface lifts a mechanically fastened single-ply roof membrane.

liquid water is absorbed by the hydrophilic fiberboard (**Figure 9**).

Other Instances of Condensation in a Roof Assembly

In a separate matter in Louisiana, the plaintiff's expert diagnosed moisture in a roof assembly as a roof leak. The roof assembly in this case consisted of a thermoplastic polyolefin (TPO) single-ply roofing membrane over polyisocyanurate insulation on a structural steel roof deck. The consultant never verified that a breach in the TPO membrane caused moisture in the roof assembly. For example, the consultant could have used a common toilet plunger to create a vacuum over suspected defects in the roof membrane. Instead, the roofing consultant removed large areas of the roof membrane, exposing the insulation.

The exposed insulation revealed moisture concentrated around fastener penetrations and along the seams of the insulation panels (**Figure 13** and **14**), reminiscent of observations in the subject warehouse case. The subject building in this case has apartment units heated/cooled using PTAC wall units. Air pressure in the units increases due to mechanically induced pressure when the PTAC units run and force outside air into the space. The apartments have no finished ceilings. The floor and roof structural members are exposed along with the steel deck. On the upper floor, air from the occupied room can be exchanged with air in the roof assembly through laps and penetrations in the steel deck.

Figure 13
Removal of a TPO roof from polyisocyanurate insulation board. Notice the dark areas indicating moisture due to condensation.

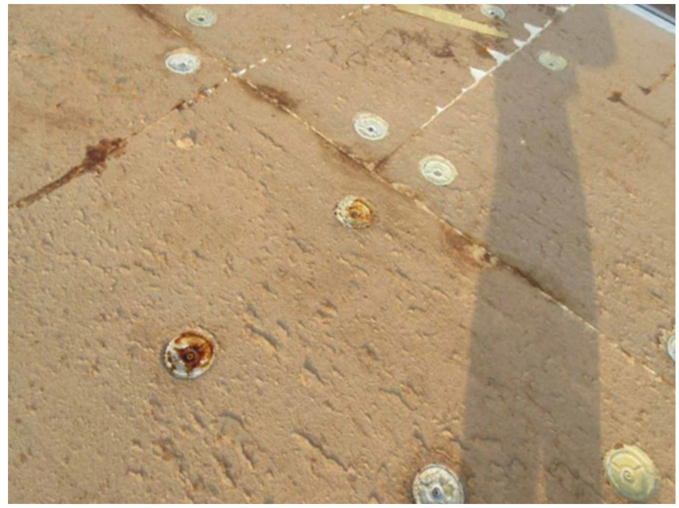

Figure 14
Detail of moisture in the polyisocyanurate insulation. Notice the concentration of moisture around seams in the insulation boards and around the mechanical attachments.

Rather than a defective roof membrane causing water to collect in the roof assembly, the photographic evidence showed that warm, humid air from the heated interior spaces infiltrated the roof assembly, where it condensed on the underside of the TPO membrane next to seams in the insulation and around mechanical roof fasteners. Moisture due to condensation was interpreted as a roof leak.

Prevention of Condensation in Roof Assemblies

The need to prevent, or minimize, condensation in roof assemblies within low-sloped roofs has been known since the 1970s[20]. However, there is no consensus regarding the use of vapor retarders. Although the current building codes require vapor retarders under various conditions for walls, slabs-on-grade, and crawl spaces, the building codes do not require vapor retarders in low-sloped roofs[21]. ASHRAE[20] and other sources[12] advise caution in the application of vapor retarders in low-sloped roofs, as it is almost impossible to prevent infiltration into the roof assembly[22]. Once condensation forms within the assembly, it is difficult to remove moisture from the roof assembly[22]. Removal of moisture from low-slope roof assemblies can only be accomplished by diffusion or wind-induced ventilation — neither of which is effective[22].

Recommendations for managing condensation in low-slope roof assemblies include:

1. Either prevent the entry of water vapor or create a system to remove the vapor or condensation[22].

2. Locate vapor retarders in the roof assembly below the point of the theoretical dewpoint temperature[23].

3. Seal the vapor retarders at the edges of roofs, at vertical projections and around penetrations to prevent short-circuiting of air barriers[24].

4. On steel decks, install low-R-value, fire-resistant insulation beneath vapor retarders to protect the vapor retarder from damage[24].

5. Install two layers of insulation with joints in the insulation offset to minimize leakage and to increase the rigidity of the insulation layer[24].

6. Install roof vents to relieve pressure due to temperature changes and provide a means for moisture to escape from the assembly.

Conclusions

The aforementioned investigations — reinforced by the principles of thermodynamics and wind engineering — support the theory that warm, humid air infiltrates into low-sloped roof assemblies. Low-sloped roof assemblies consisting of roof membrane over rigid insulation and steel roof deck allow warm moist air to migrate through the components of the roof and condense on the underside of the roofing membrane. Regardless of the type of insulation used, the condensation is absorbed by, and retained within, the insulation. However, when the insulation board contains corrosive constituents, such as acetic and formic acid found in bagasse fiberboard, the moisture dissolves the corrosive material, and the accumulation of acidic solution deteriorates the steel deck and fasteners at an accelerated rate.

The condition most conducive to moisture collection in the roof assembly is characterized by cool roof surfaces over warm, humid interior spaces. This suggests that the phenomenon may not be confined to southern, costal portions of the United States but may also occur where the interior space is artificially heated and humidified. Based on these findings, the recommended construction for low-sloped roof assemblies consisting of a layer of rigid insulation sandwiched between a roof membrane and a steel deck should be as follows:

- Install two layers of the insulation board with their seams staggered and taped. This increases the rigidity of the roof membrane where the insulation boards abut over the ribs of the deck, making the roof more resistant to damage from foot traffic and blocks the pathway from the steel deck to the roof membrane.

- Prevent the infiltration of air from the interior of the building into the roof assembly by installing a vapor barrier on top of the steel deck and/or seal joints and laps in the steel deck.

- Add pressure relief valves through the roof membrane to prevent buildup of pressure due to heating and cooling and to vent any moisture that collects in the roof assembly.

If these modifications to the roof assembly design had been employed in the assemblies investigated in this case, damage to the roofs insulated with bagasse insulation may have been avoided — and bagasse fiberboard might still be available as a viable, sustainable, and economic insulation material. Regardless of how low-sloped roofing systems are insulated, moisture in the assembly deteriorates the roofing components. Based on the findings of this investigation, managing condensation in low-sloped roof assemblies requires rigorous attention to the design of roof assemblies and consideration of local climatic conditions.

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