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* Paper presented at the NAFE seminar held 1/14/17 in New Orleans, LA

‡ Paper presented at the NAFE seminar held 7/22/17 in Atlanta

Advanced Technologies Utilized in the Reconstruction of an Officer-Involved Shooting Incident

By Richard M. Ziernicki, PhD, PE (NAFE 308F) and Angelos G. Leiloglou (NAFE 956C)

Abstract

This paper presents a case study that utilized many of the latest forensic technologies to reconstruct the events that occurred during an officer-involved shooting incident in which a police officer fatally shot a fellow police officer. The shooting reconstruction utilized 3-D high-definition laser scanning, "matchmoving" of police helicopter infrared video footage, motion capture, photogrammetry, creation of a 3-D interactive virtual shooting scene, and virtual reality display systems. It also outlines how the trajectory of bullets were reconstructed, and how the position and posture of the shooting officer and victim officer were determined. Finally, federal judge rulings on various Daubert motions (509 U.S. 579 [1993]) to exclude or limit testimony of expert witnesses are presented.

Keywords

Police-involved shooting, bullet trajectory, 3-D laser scanning, matchmoving, motion capture, photogrammetry, forensic engineering, videogrammetry, virtual reality, Daubert

Introduction

An officer-involved shooting incident occurred at night, during a police investigation related to gunshots reported in a residential area. Officer Dole*, a 35-year-old male police officer, was looking over a privacy fence that separated two properties when he was shot by a fellow officer (Officer Baker*). Officer Baker fired six rounds at Officer Dole, striking him once in the head and killing him.

The fundamental questions posed to the authors were:

1. What was the order of the shots fired?

2. Which shot was the fatal shot?

3. What was Officer Dole's position and posture when Officer Baker shot him?

4. What was Officer Baker's view of Officer Dole when he shot him?

* Officers' names used are fictional.

Procedure

To answer those questions, a reconstruction of the shooting incident was conducted by the authors who reviewed the physical evidence documented by the police at the shooting scene and used some of the latest forensic technologies to properly reconstruct key components of the shooting scene and perform an accurate virtual bullet trajectory analysis of the shots fired by Officer Baker.

The reconstruction included an inspection of the shooting site that involved using high-definition laser scanning technology[++] to capture and document the area and all available evidence. The highly accurate, 3-D data collected in the form of a point cloud was used to create an interactive, 3-D virtual model of the shooting scene. This virtual shooting scene model was used to perform bullet trajectory analysis and determine:

(a) The position and posture of Officer Dole,

(b) Officer Baker's position, and

[++] The authors used a Faro Focus 3D laser scanner (www.faro.com).

Richard M. Ziernicki, PhD, PE, and Angelos G. Leiloglou, 7185 S. Tucson Way, Centennial, CO 80112, 303-925-1900, rziernicki@knottlab.com, aleiloglou@knottlab.com

(c) What Officer Baker could likely have seen at the time of the fatal shooting.

The point cloud also enabled the authors to use photogrammetry on police photos to accurately document and reconstruct evidence that had been removed from the scene. The point cloud was also used with a videogrammetric process called "matchmoving" that was performed on provided police helicopter video footage, which showed the position and posture of Officer Dole for a period of time prior to the shooting.

The matchmoving process was used to solve for the properties and 3-D path of the moving police helicopter camera relative to the point cloud of the shooting site. The photogrammetry and videogrammetry, combined with the virtual bullet trajectory analysis, allowed the authors to determine the probable location and posture of Officer Dole along the fence as well as where Officer Baker was and what he could likely see at the time of the shooting.

Finally, the primary author's analysis and opinions passed all Daubert‡ challenges by the defense, while the testimony of some other experts was limited by the judge.

Background

At approximately 2 a.m., the police department was called to a home in a residential area (labeled in red in **Figure 1**) on the report of shots fired. Police officers from other metro jurisdictions also responded to the call. A total of 29 police officers and a police department helicopter with Forward Looking Infrared Radar (FLIR) video responded.

One of the responding officers witnessed a person step out of an exterior door on the north side of the residence

Figure 1
Aerial view of the residence.

Figure 2
Aerial map of shooting area.

into the carport area (see black dot labeled with a red X in **Figure 2**) of the single-story residence, fire a gun, and return inside.

Police determined that the residence had three occupants who were contacted by police and ordered to vacate the residence through the front door — which they did. At around that time, Officer Dole and another officer positioned themselves in the area to the north of a wooden privacy fence that bordered the north side of the residence (see **Figure 2**). Both officers could look over the fence by standing on an aluminum extension ladder that was on the ground horizontally and leaning against a chain-link fence immediately north of the wooden privacy fence (**Figure 3**).

Other officers had moved to the front door of the residence and requested additional officers to assist in clearing the house. The officer who was with Officer Dole, north

Figure 3
Extension ladder on the north side of the wooden privacy fence, bordering the residence.

‡ A Daubert challenge is a hearing before the judge where opposing counsel challenges the admissibility of expert testimony.

Figure 4
Panoramic image of carport area "stitched" together from four police investigation photos.

of the privacy fence, left his position and joined the other officers who entered the house and cleared the front rooms of the house.

Officer Baker, who was responding to the call for assistance, arrived on the scene at around 3:15 a.m. and joined the officers who were clearing the house. A decision to visually clear the remaining rooms from the outside was made; Officer Baker and two other officers dressed in full SWAT gear and armed with rifles exited the north side of the house through a door that led to the carport area and into the backyard, which had not yet been cleared (**Figure 4**).

Based on Officer Baker's testimony, upon exiting the house, Officer Baker went immediately to the left, took a few steps toward the west, and cleared the area to his left. Then Officer Baker moved out toward the north (to the left of the northwest carport post) and began to visually scan from his left to his right. As Officer Baker "pied"± around the post with his Bushmaster AR15 rifle, he reportedly heard a voice from the area of the privacy fence to the north say: "Hey."

Officer Baker activated his rifle-mounted light and scanned to his right and made visual contact with the person. Officer Baker could see the person's left hand, head, and right hand up over the top of the fence. Officer Baker testified that he saw a black semi-automatic handgun in the person's right hand and yelled, "Police, drop the gun, drop the gun." Officer Baker then fired six rifle rounds at the person on the fence. The person fell back away from the fence, and Officer Baker stopped shooting. The shots were fired at around 3:48 a.m.

Later, the person that was down was identified as Officer Dole. His body was found positioned on his back on the north side of the privacy fence with his head toward the apartment building with his feet still in contact with the ladder on which he had been standing. A paramedic was brought onto the scene and pronounced Officer Dole deceased. Officer Dole had a gunshot wound just below his left eye with an exit wound on the back, lower left side of his head (**Figure 5**).

Officer Dole's handgun and flashlight were found on the south side of the privacy fence. The magazine from the handgun was not inside the gun but was found along with one live round from the magazine near the handgun and flashlight (**Figure 6**).

Site Inspection

In conducting the shooting reconstruction, the authors performed an inspection of the site to collect information

Figure 5
Officer Dole's final resting position.

Figure 6
Police photo of Officer Dole's Glock 17 (Gen 4) handgun (#14), gun magazine (#15), one live 9-mm round (#16), and flashlight (#17) found on the south side of the privacy fence.

± "Pie-slicing" or "slicing the pie" is a tactical technique that allows the slow, gradual observation around a corner or other obstacle.

Figure 7
Point cloud of the shooting site captured by the authors with a Faro Focus 3D high-definition laser scanner.

pertinent to the investigation. The inspection, one year after the shooting incident, consisted of measuring, photographing, and using high-definition laser scanning technology to scan the shooting site to document the available physical evidence, obtain accurate measurements (for the purpose of bullet trajectory analysis), and reconstruct the shooting. The highly accurate (within a few millimeters) data was collected by a Faro Focus 3-D scanner and consisted of more than 400 million 3-D data points, collectively called a "point cloud," as shown in **Figure 7**.

Evidence Documentation

During the site inspection, the authors photographed, measured, and scanned five bullet marks, which were visible on the southern exterior wall of the neighboring two-story apartment building. The five marks present were consistent with marks documented during the police investigation (**Figure 8**). The police had documented two other marks on a portion of a downspout that had since been removed and was not available during the inspection.

In addition to the marks on the brick wall, the authors also photographed, measured, and scanned a single hole in the wooden privacy fence and a scuff mark on the concrete footing below the fence, possibly left by Officer Dole's handgun as it was released and fell to the ground (**Figure 9**).

By using high-definition laser scanning technology in their inspection, the authors were able to capture a vast point cloud that documented the entire shooting scene, including all available evidence marks. The level of detail and degree of accuracy of the point cloud allowed the authors to apply various accepted scientific methods (photogrammetry, videogrammetry, and bullet trajectory analysis) to the data with a very high degree of engineering certainty.

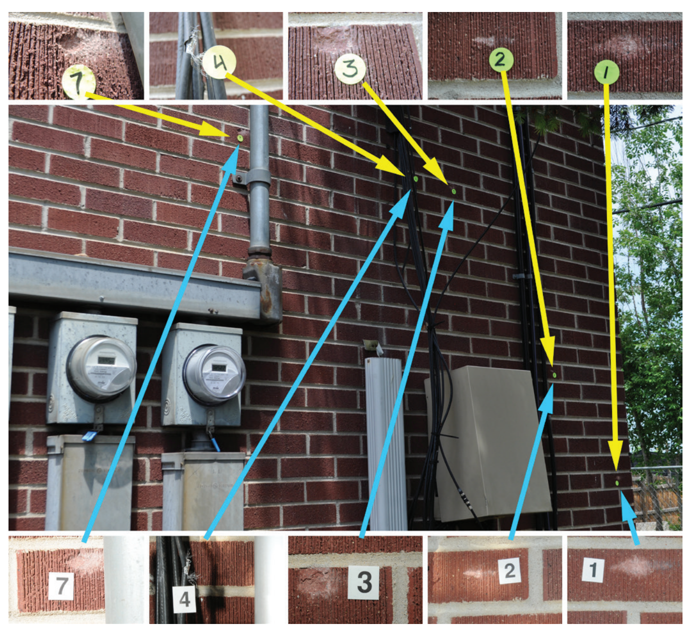


Figure 8
Marks on southern wall of apartment building left by bullets (middle); the authors' inspection photos (top); and police photos (bottom).

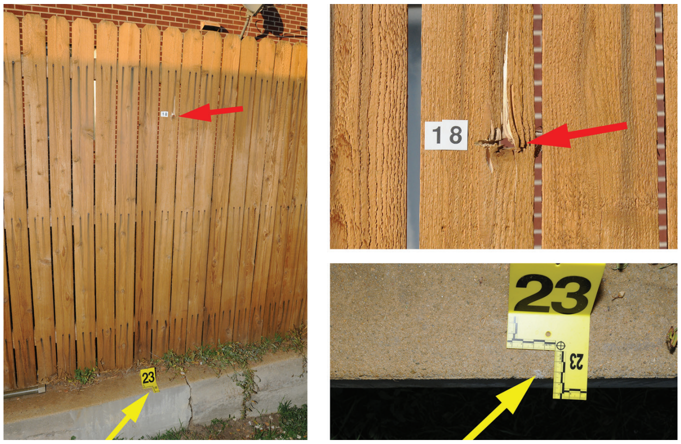


Figure 9
Single bullet hole in wooden privacy fence picket (red arrow); scuff mark on concrete footing (yellow arrow).

Photogrammetry Analysis

As part of the reconstruction, the authors performed photogrammetry on police photographs in order to properly reconstruct key components of the shooting scene, including the carport, the tarp that was hanging on the north side of the carport (which had been removed prior to the authors' inspection), the position of the vehicle under the carport (**Figure 10**), the resting position of Officer Dole's body (**Figure 11**), his handgun, the magazine from his handgun, the live round from the magazine, and his flashlight.

Video Analysis

The authors also performed videogrammetry on provided video footage captured by the police department helicopter's FLIR camera, which detects heat. In the video, Officer Dole was seen standing in an upright position on the aluminum extension ladder as the helicopter circled the shooting scene. Using data from the point cloud of the shooting site, a scientific process called "matchmoving" (also called "camera tracking") was used to define a virtual camera that "matches" the location, orientation, focal length, and lens distortion of the camera used to record the provided video footage.

Figure 10
Photogrammetry performed to determine where the carport and hanging tarp were during the time of the shooting.

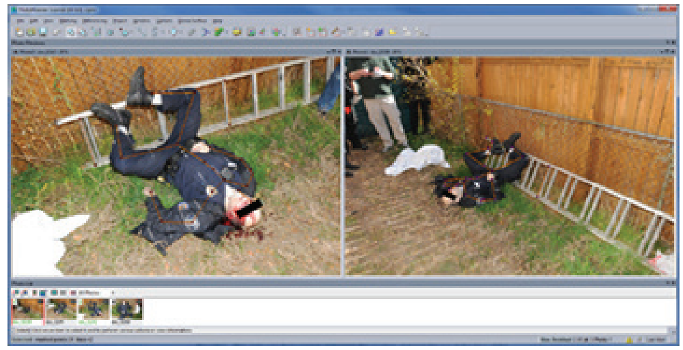


Figure 11
Photogrammetry performed on police shooting scene photos of Officer Dole's final resting position after being shot.

Using specialized software (SynthEyes by Andersson Technologies), 2-D points ("features") were identified and tracked through multiple frames of the video. Each feature represented a specific point on the surface of some fixed object in the shooting scene (i.e., fence posts, roof corners, vents, windows, etc.). Each tracked feature was then assigned and constrained to the feature's corresponding 3-D coordinates (x, y, z) as defined by the shooting scene point cloud. The software then mathematically solved for ("calibrated") a virtual camera (within the virtual shooting scene), which emulated the real-world camera that was used to record the video footage.

While viewing the 3-D shooting scene through the lens of the solved virtual camera, a computer-generated, 3-D character model of Officer Dole was inserted into the scene to accurately mark the position of Officer Dole along the fence as seen in the video (**Figure 12**).

Virtual Interactive Shooting Scene

The authors created a highly detailed and accurate 3-D computer model of the shooting scene based on the point cloud captured during the authors' inspection of the shooting site. The computer model, along with data attained through the photogrammetry and videogrammetry, was combined into an interactive virtual environment, which is shown in **Figure 13**. The interactive virtual environment allowed the authors to move around and view the virtual shooting scene from any vantage point, perform bullet trajectory analysis, test/analyze the position/pose of Officer Dole on the fence, and test/analyze the position of

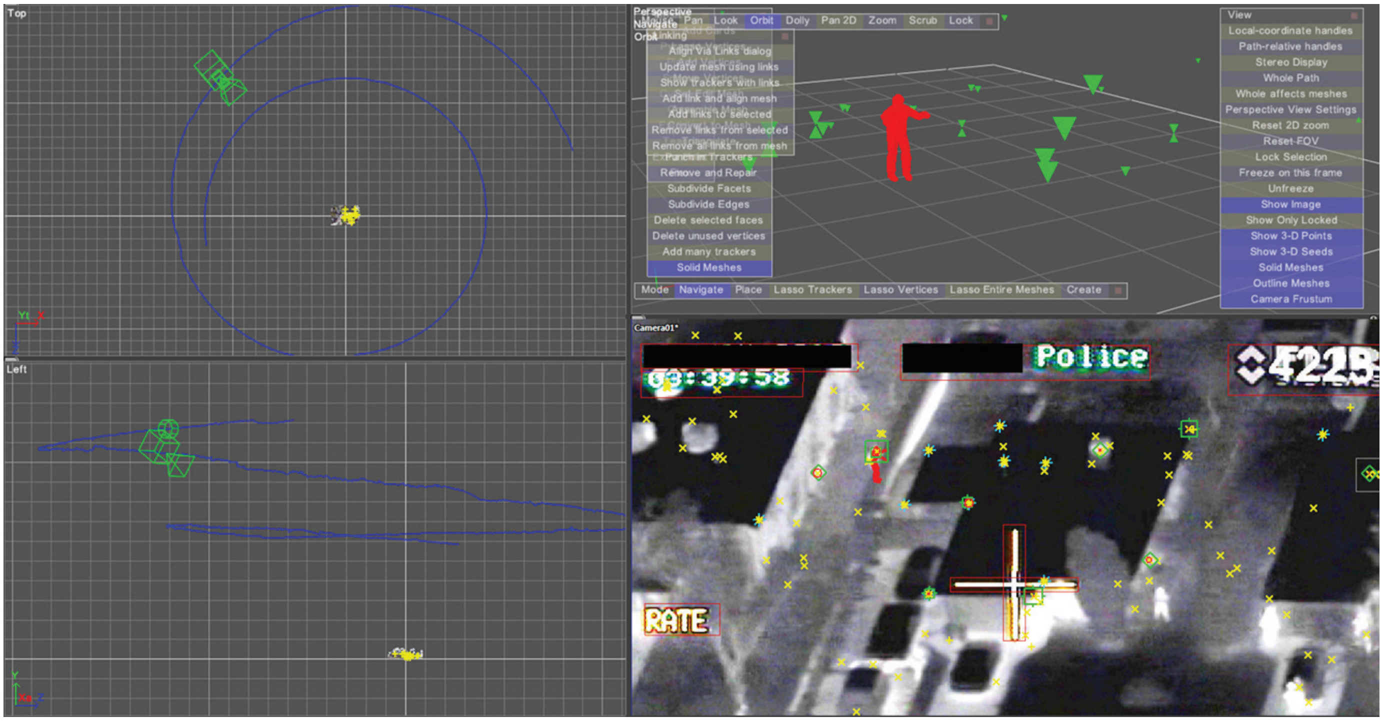


Figure 12
Camera match of provided police helicopter video footage.

Figure 13
Interactive 3-D virtual shooting scene based on point cloud from HD Laser Scanning (shown on the right).

Officer Baker during the shooting.

Bullet Trajectory Analysis

According to the police investigation of the shooting scene, six .223 (5.56-mm) caliber spent casings from Officer Baker's rifle were found in the carport area near the north-facing exterior door and the rear of the parked vehicle. The general location of the six casings was consistent with an AR15's right-facing ejection port and the area where Officer Baker was reported to be when he fired his rifle at Officer Dole.

The virtual model of the shooting scene included accurate locations of all the evidence items on the southern exterior wall of the apartment building documented by the authors, as well as the precise location of the bullet hole in the wooden privacy fence (#18) and scuff mark left by the falling handgun on the concrete footing (#23). A digital model of the portion of downspout, which was missing at the time of the inspection, was added to the virtual shooting scene model, and evidence marks #5 and #6 were located using photogrammetry techniques on police scene photos.

The virtual shooting scene model allowed the authors to perform an accurate bullet trajectory analysis by connecting evidence items on the brick wall and evidence item #18 (the bullet hole in the privacy fence) back to a point representing the end of Officer Baker's rifle, approximately 62.5 inches off the ground at the location where Officer Baker was determined to be standing at the time of the shooting (**Figure 14**). This height was estimated by police in their initial investigation using a trajectory rod and string. The authors also confirmed this by posing a virtual surrogate model in the same shooting stance Officer Baker demonstrated during a video-recorded deposition.

The authors utilized the virtual shooting scene to analyze the evidence, and made the following findings. Note

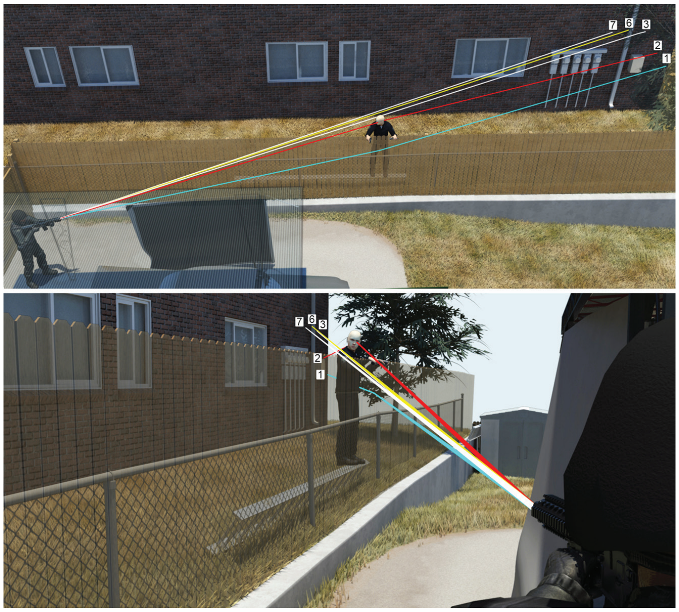


Figure 14
Bullet trajectory analysis performed in interactive virtual shooting scene.

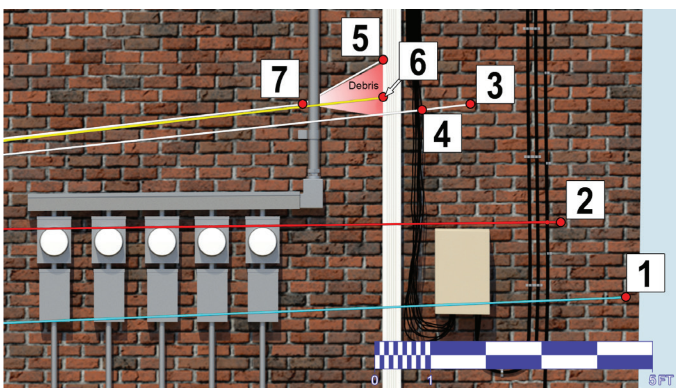


Figure 15
Evidence matched to bullet trajectories.

Figure 16
The gouge mark on the vertical cable and the mark on the wall at evidence item #2 are at the same elevation, indicating a relatively horizontal trajectory for the bullet that made these two marks.

that all described bullet marks were confirmed as being made by bullets by the police crime laboratory, but DNA test results of the marks (if any were obtained) were not revealed in discovery.

Evidence Item (see **Figure 15**):

- #1 – Mark on brick wall made from a bullet. This mark on the wall was below the elevation of the top of the privacy fence and the lowest mark left on the wall.
- #2 – Mark on brick wall made from a bullet. Before hitting the wall, the bullet clipped and left a gouge mark on a vertical cable fixed to the wall. These two marks (gouge mark on cable and mark on wall) were at the same elevation (**Figure 16**), indicating a relatively level trajectory for the bullet that made these two marks.
- #3 and #4 – A bullet made a mark on a vertical cable (#4) and then left a mark on the wall (#3).
- #5 – Mark on downspout made from ricocheted bullet after hitting the wall and leaving a mark at evidence item #7.
- #6 – A group of holes and marks in the downspout. Some of the holes and damage are made from debris from the bullet contact at evidence item #7. One to two of the holes may have been made by one or two of the shots fired (not the bullet that created the debris).
- #7 – Mark on wall made from a bullet, which then ricocheted, leaving evidence item #5 on downspout.
- #18 – Bullet hole in fence.
- #23 – Scuff mark on the concrete footing below the fence created by Officer Dole's handgun as it fell to the ground on the south side of the fence.

Based on the authors' bullet trajectory analysis, Officer Baker's height, a normal shooting stance, and the angle of the bullet penetration through the fence, the authors confirmed that the shot fired through the fence was done from a rifle muzzle at a height of approximately

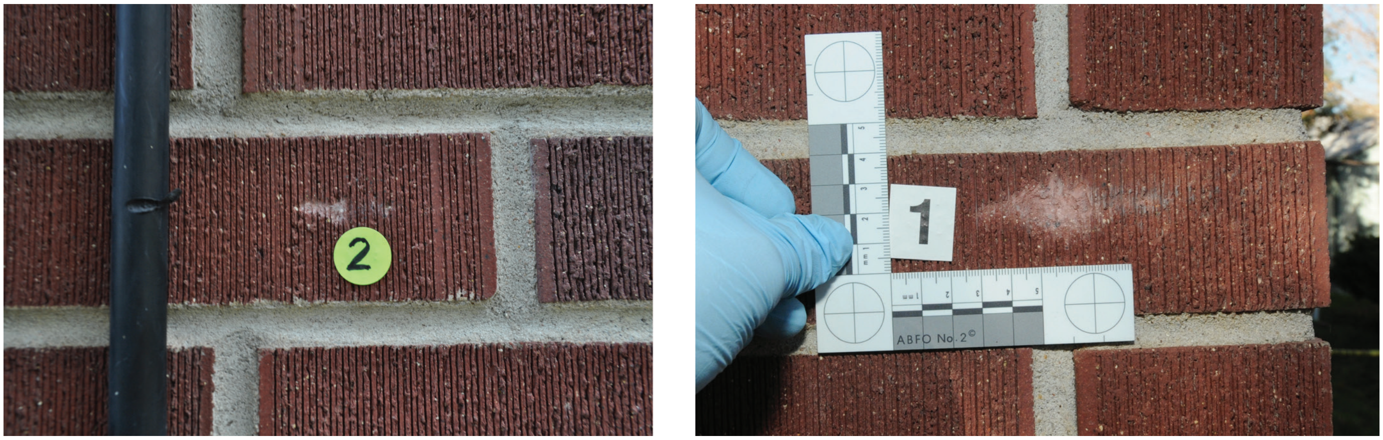


Figure 17
Horizontal bullet mark left at evidence item #1 and relatively horizontal mark left at evidence item #2.

62.5 inches above the ground, which agreed with the police investigation.

The authors also determined that the bullets that left marks for evidence items #3, #4, #5, #6, and #7 were shot above the fence from Officer Baker's shooting position. Furthermore, one of the two bullets that left the marks for evidence items #1 and #2 on the wall passed through the privacy fence, and the other bullet passed through Officer Dole's head. Both of these bullets were deflected as they passed through Dole's head and the fence, respectively.

The marks at evidence items #1 and #2 are both relatively horizontal marks on the wall (**Figure 17**), indicating that the bullets that left those marks had relatively level trajectories, which can be true of destabilized, deformed, and even tumbling, exiting bullets over short distances[1].

As mentioned, evidence item #2 was made after the bullet clipped and left a mark on a vertical cable at the same height as the mark on the wall. The height of evidence item #2 is consistent with a trajectory above the fence, while the height of evidence item #1 is consistent with a trajectory through the fence. Therefore, the authors determined that the bullet that passed through the fence (#18) left evidence item #1, and the fatal bullet that passed through Officer Dole's head clipped the vertical cable and left evidence item #2.

The authors were able to account for the four bullets that corresponded with evidence items: #1, #18, #2, #3, #4, #5 and #7. However, the authors were not able to positively account for the remaining two bullets (out of six) that were fired. Either both missed the apartment building wall, one of them missed the wall and the other hit the downspout (at evidence mark #6), or both hit the downspout.

Shot Timing Analysis

During an interview with an investigating detective, Officer Baker stated:

"*Um, so I fired uh, I had been holding the uh, my site, my optic, my rifle on the person's uh, head. When I saw the gun come up, urn, I thought I was gonna get shot. I fired my first round urn, at the person's head, urn, and then as I was — as soon as I fired that first round, uh, I think I began kind of retreating backwards, urn, just to try to get some distance and some kind of cover, and as I was doing that I transitioned down to the person's torso which uh, would've been just on the other side of the fence, just, you know, lowered my, my point of aim just a few inches. Urn, I fired I believe, four additional rounds. Urn, and as the person you know, fell back away from the fence, urn, I couldn't see him anymore. I at that point, he threw the gun away so I stopped firing.*"

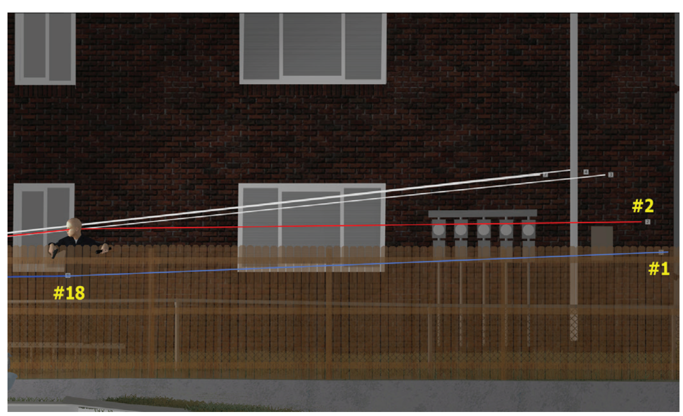


Figure 18
The authors' bullet trajectory analysis determined the bullet (red), which left mark #2 on the wall, was the bullet that passed through Agent Dole's head, and the bullet that left mark #1 was the bullet that passed through the fence (blue).

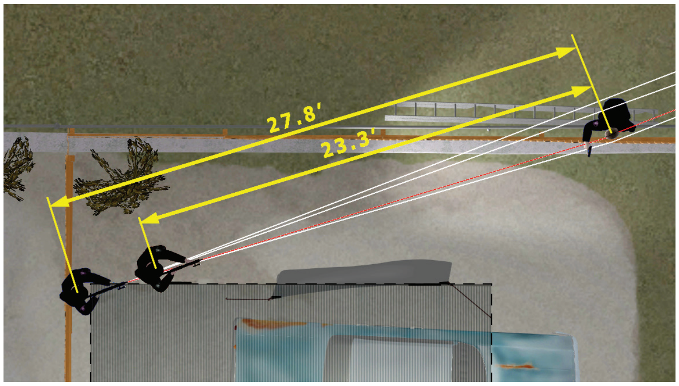


Figure 19
Range of positions Officer Baker was while firing the shots, as determined by the authors.

Considering the physical evidence, bullet trajectory analysis, and the statements made by Officer Baker, the authors determined that:

- Officer Baker fired a total of six shots.
- The first shot fired was the fatal shot (this was the consensus of all involved experts) and left mark evidence item #2 on the apartment building wall, as shown in **Figure 18**.
- One of the five remaining bullets passed through the fence (evidence item #18) and left mark evidence item #1 on the apartment building wall.
- All remaining four bullets were shot above the fence line.

The Shooter's Position and Motion Analysis

Considering the available evidence, the authors used the virtual shooting scene and bullet trajectory analysis to determine the range of positions Officer Baker could have been while firing the shots. The authors determined the nearest and furthest distance Officer Baker was from Officer Dole (while shooting) to be 23.3 feet and 27.8 feet, respectively (**Figure 19**). The nearest distance was determined by moving Officer Baker in the virtual scene as close to Officer Dole without the bullet trajectories of the bullets, which left evident marks #3-#7 on the brick wall, hitting the fence. The farthest distance was determined by moving the virtual Officer Baker back until he was restricted by the fence behind him (**Figure 19**).

Shot Officer's Position/Posture/Pose Analysis

To reconstruct the horizontal position where Officer Dole was along the fence, moments before Officer Baker shot him, the authors used photogrammetry performed on provided police photos of Officer Dole's body, lying on the ground, after he was shot to determine where his feet were on the ladder and where the ladder was in respect to the privacy fence. Additionally, the authors used the scuff mark on the concrete footing, likely left by Officer Dole's handgun, to place Officer Dole's right hand on the fence.

Figure 20
Still frame from police department helicopter FLIR video footage, showing Officer Dole standing upright, positioned with his right arm on the wooden privacy fence prior to the shooting. Zoomed view by the authors.

To reconstruct Officer Dole's posture, the authors first used the video analysis of the provided police department's helicopter video footage, which showed that Officer Dole was standing straight up, maintaining his position on the ladder for the entire time he can be seen by the camera, which was a total of approximately half of the 20-minute video. Officer Dole is intermittently occluded by the two-story apartment building as the police helicopter is circling the scene. Furthermore, when the video camera zooms in, at various times throughout the video, Officer Dole can clearly be seen standing with his left and/or right hand on top or over the fence, as shown in **Figure 20**.

Secondly, the authors matched the exit wound on the back of Officer Dole's head with the trajectory of the fatal bullet that left the gouge mark on the vertical cable and then left evidence mark #2 on the brick wall.

Thirdly, in conducting analysis and assessment of Officer Dole's position, posture, and pose at the time of the shooting, the authors placed, within the virtual shooting scene, a virtual character model of the same height and body type as Officer Dole, on top of the ladder in

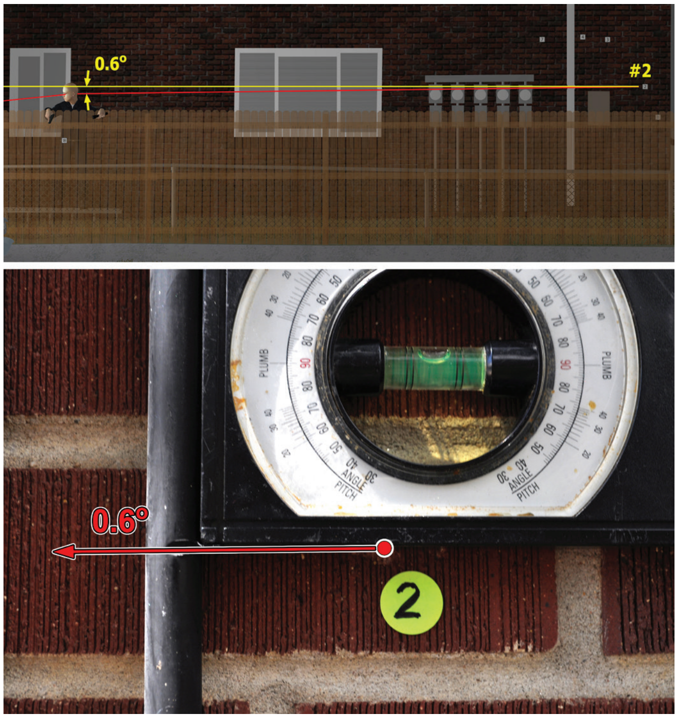


Figure 21
The trajectory of a bullet leaving the back of Officer Dole's head from an elevation defined by the authors' shooting reconstruction and leaving a mark at evidence item #2 was consistent with the physical evidence.

the lateral position along the fence (determined through photogrammetry and videogrammetry) as discussed previously. The authors posed the virtual character to be standing up and then connected the exit wound on the back of Officer Dole's head to the bullet mark at evidence item #2 on the wall. The trajectory line passes through the gouge mark on the vertical cable and is consistent with a relatively level trajectory indicated by the horizontal mark of the fatal bullet, as shown in **Figure 21**.

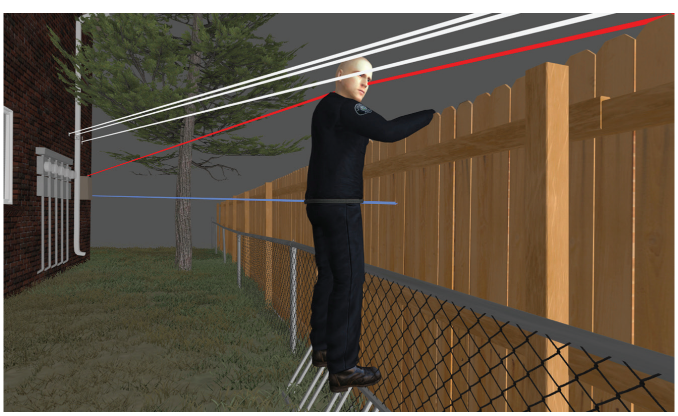


Figure 22
Probable position, posture, and pose of Officer Dole as determined by the authors. View from the north side of the wooden fence.

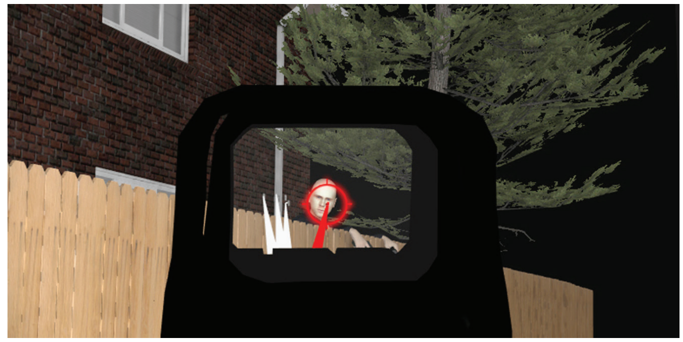


Figure 23
View from Officer Baker's point of view of Officer Dole at the time of the shooting, as determined by the authors.

The elevation of Officer Dole's head in the position/posture/pose determined by the authors (**Figure 22**) is consistent with the physical evidence, which indicates a relatively level trajectory of the fatal bullet exiting Officer Dole's head, clipping the cable and leaving the mark at evidence item #2, as previously discussed and shown in **Figure 18**.

Once the reconstruction was completed, the authors were able to determine what Officer Baker should have been able to see from his point of view when he first saw Officer Dole and then fired six times, fatally striking Officer Dole in the head (**Figure 23**).

Daubert Challenges

While the defense agreed with some of the authors' conclusions regarding the shooting, they claimed that the authors' expert report conveyed a false level of precision with regard to their analysis based on the use of various technologies, specifically high-definition laser scanning.

The defense also argued that in concluding Officer Dole's head location was above the fence, the authors did not determine or take into account the amount of deflection of the bullet as it passed through Officer Dole's head, and that the authors were solely basing their conclusion on "extrapolating" a bullet path angle from the alignment of bullet strike mark #2 on the brick wall to the gouge on the adjacent cable. The defense argued that such a calculation would have limited precision because the amount of deflection from passing though Officer Dole's head was unknown, and the angle of the bullet path afterward cannot be determined to a high level of precision.

As discussed above, the deflection of the bullet as it traveled through Officer Dole's head is irrelevant in determining the path the bullet took upon exiting Officer Dole's head. All that is required in determining the path of the bullet in 3-D space is three points, working backward: 1) mark on the brick wall; 2) gouge in vertical cable; and 3) exit wound on the back of Officer Dole's head. The defense also claimed that the author's analysis of video footage taken 40 minutes prior to the shooting was irrelevant to Officer Dole's position at the time of the shooting.

The judge ruled:

"The judge denied [the defendant's] motion to exclude or limit expert testimony of Dr. Richard Ziernicki. The judge found that helicopter video of [Officer Dole] standing in an upright position on a ladder and remaining in the same location and position throughout the video footage was one objective physical fact that was used to test and confirm Ziernicki's opinion that [Officer Dole] was probably standing upright on the ladder when he was shot."

"[Officer Dole's] positioning and movements, including where and how he was holding his weapon, immediately before he was shot are important facts in this case. Apparently, the shooter is the only available eyewitness to these facts. But one must bear in mind that by connecting the marks on the wall and adjacent cable, and the exit wound, he [Ziernicki] can determine where [Officer Dole's] head was when the shot was fired. One can agree or disagree with his opinion, the judge said[2]."

Virtual Reality Technology

By utilizing an Oculus Rift[3] virtual reality headset (shown in **Figure 24**), the authors were able to interactively navigate and experience the virtual shooting scene from an immersive, first-person point of view as shown in **Figure 25**. This technology creates stereoscopic 3-D

Figure 24
Oculus Rift Virtual Reality headset used to view the interactive virtual shooting scene.

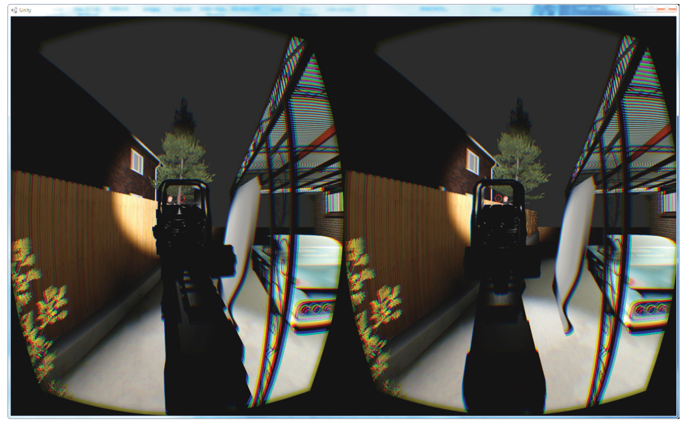


Figure 25
Immersive (stereoscopic) first-person shooter point of view in the interactive, virtual shooting scene developed by the authors.

views, which provided the authors a powerful tool to accurately simulate and test a range of possible positions/poses that Officer Dole was in as well as the range of locations Officer Baker was shooting from.

Conclusions

After the investigation was completed, the authors were able to answer questions regarding the order of shots, which shot was fatal, the position and posture of Officer Dole, and more.

This case study demonstrates the application of some of the latest technologies and methodologies used during the reconstruction of an officer-involved shooting incident. Such technologies, when used properly, can be effective for accurately reconstructing bullet trajectories and for analyzing surveillance video footage. Finally, these technologies and their use in shooting reconstruction (for this case) were validated and held up against Daubert challenges in court.

References

1. Haag M, Haag L. 2011. Shooting incident reconstruction. 2nd edition. Amsterdam: Academic Press.

2. http://www.lexislegalnews.com/articles/6148/judge-rules-on-daubert-motions-in-lawsuit-over-police-officer-shooting

3. https://www.oculus.com/

Bibliography

Ziernicki R, Johnson W. Forensic Engineering Techniques to Reconstruct Shooting Incidents. Journal of the National Academy of Forensic Engineers. 2001; 18(1).

Ziernicki R, Pierce W, Leiloglou A. Forensic engineering usage of surveillance video in accident reconstruction. Journal of the National Academy of Forensic Engineers. 2014; 31(2):9-19.

Klasen L, Fahlander O. Using Videogrammetry and 3D Image Reconstruction to Identify Crime Suspects. Investigative Image Processing. 1997; 2942.

Forensic Engineering Analysis of Alleged Construction Defects

By Michael Stall, PE (NAFE 955M)

Abstract

Information from visual forensic inspections is often used to conclude that building performance failures are caused by construction deficiencies because visual observations are limited to current conditions that seem to indicate that construction is the only cause. Design issues, constructability, product failures, adverse or abnormal weather conditions, post-construction changes, code and ordinance contradictions, lack of maintenance, abuse or neglect, and construction deficiencies contribute to building performance failures. Detailed investigation, coupled with visual observation, is required to understand failures and fairly assign liability.

Keywords

Building performance, building code, construction defect, changed conditions, design defect, conflicting regulations, forensic engineering

Analysis of Alleged Construction Defects

When property owners perceive that buildings have construction defects and retain attorneys to provide their day in court, the forensic engineer must evaluate each alleged defect (in the context of how building performance was affected by project team members) and not jump to the conclusion that all building performance issues are builder defects. In addition to identifying actual construction defects, the forensic engineer also should consider what effect each participant could have on the design, procurement, and building process. **Figure 1** demonstrates how the more important participants can affect building performance.

Each participant in the design, procurement, and construction process should have the goal of creating a code-compliant building that provides good value during its life cycle. However, they do not always succeed, often creating defects that become apparent years after the building is completed — defects a superficial visual observer could conclude are caused by the builder. A thorough forensic engineering analysis must consider the following major issues (as applicable) when evaluating alleged defects:

- Design mistakes, code and ordinance contradictions, constructability, material failures, adverse weather conditions, post-construction changes, neglect and

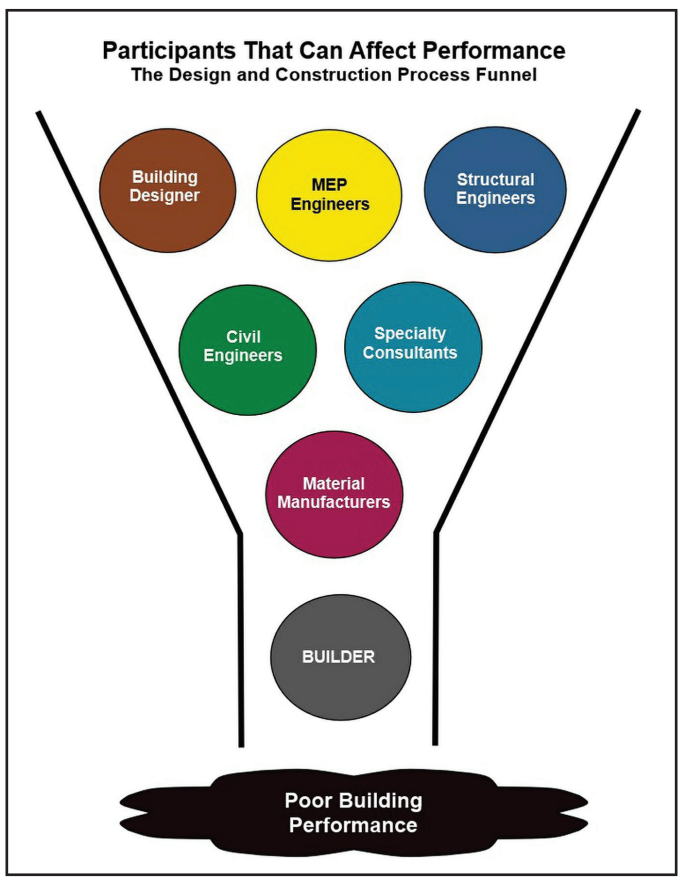


Figure 1
Parties affecting building performance.

Michael D. Stall, PE, 77 Sugar Creek Center Blvd., Suite 210, Sugar Land, Texas 77478, 713-906-0181, mike@mribuilds.com

Figure 2
Defective connection.

maintenance failures, abuse, and actual construction defects contribute to building failures.

- Broad spectrum and detailed historical investigation from design and procurement through construction and maintenance, coupled with current visual observation and assembly testing, may be required to understand which party is responsible for the failures.

It is important to consider these issues as a basis for forensic analysis of building performance to ensure the forensic analysis is diligent, thorough, and accurate.

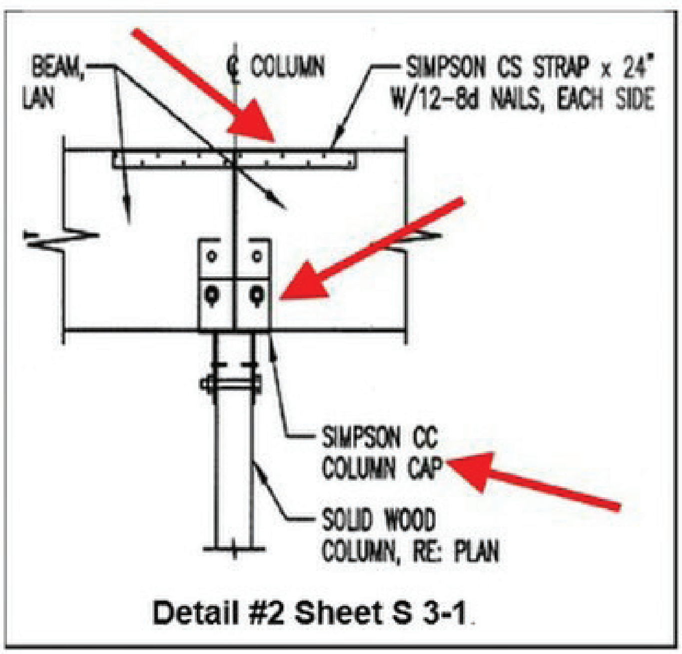


Figure 3
This is how the connection in Figure 2 was designed.

Basic Builder-Caused Construction Defects

Figure 2 shows a builder-caused defect where the column-to-beam connection was not constructed as it was designed.

Figure 3 is the applicable drawing detail that specified the required column cap, which was not installed by the contractor. There was no mystery in the design, and there was no logical reason why the specified column cap was not installed by the builder. The possible future observable defect would be a distressed or failed connection after a wind storm of sufficient magnitude to stress the defective connection. **Figure 4** provides another example of a builder-caused defect where this post foundation was not constructed as designed — with the wood post being directly embedded in concrete. **Figure 5** shows the drawing detail that specified the required foundation configuration and anchor.

There was no configuration mystery because the design illustrated how the post was supposed to be connected to the concrete. The future defect will be a rotten column because water will seep through the bricks and not drain away from the wood post. These two examples show contractor mistakes that could lead to serious hidden damage during the building's life cycle.

Figure 4
Incorrect configuration.

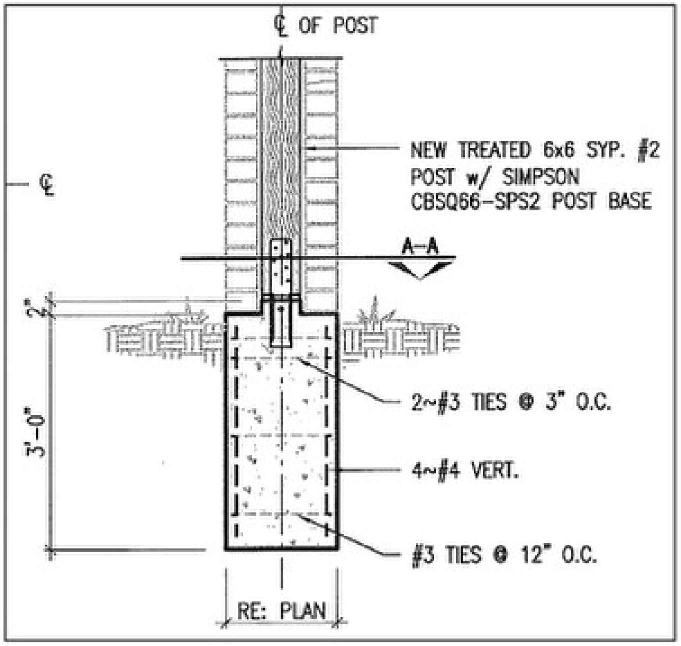


Figure 5
This is how the connection in Figure 4 was designed.

Figure 6 shows a condition where the contractor failed to provide sufficient concrete cover over reinforcing iron in a high-corrosion environment located near the Gulf of Mexico. Visual observations, coupled with investigation of project documentation, revealed how this mistake occurred. The contractor failed to detail and fabricate the horizontal reinforcing column bands correctly, which resulted in more than 500 columns being compromised because of insufficient concrete cover over the bands.

Figure 7
Missing bolts.

Since this was a corrosive environment near the beach, the lack of extra concrete cover as specified by the American Concrete Institute (ACI) for corrosive environments resulted in accelerated corrosion and deterioration.

The following examples show what can appear to be defects caused by the builder, but that could have actually stemmed from some other cause. **Figure 7** appears to show how the builder failed to install bolts in this flight of stairs. Or does it show that the bolts are missing six years

Figure 6
Insufficient concrete cover over reinforcing iron results in corrosion.

Figure 8
Questionable caulking.

after construction, two years after a hurricane damaged the property, and after extensive repair work was done? The visual observation could lead to the conclusion that the builder failed to install the bolts. The detailed forensic evaluation, however, would look beyond what is visible. For example, if removal of the stairs was included in the hurricane damage repair scope, that would likely eliminate the original builder as the cause of these missing bolts.

Figure 8 demonstrates a non-workmanlike caulking application. Based on a visual observation, one could conclude that the builder made a mistake, but that could be wrong. This could be a post-construction hurricane repair activity, the building could have been recaulked and painted, or a condominium owner could have done this. Interviewing the condominium owner, evaluating the layers of paint, researching condominium maintenance records, and considering other information (such as construction punch lists and hurricane repair scopes) could result in the conclusion that this is a post-construction mess not caused by the builder. These two examples show either simple construction defects or deficiencies that could have been caused by activities the builder was not responsible for. The forensic engineer must keep an open mind that will evaluate all information and then make conclusions based on that information.

Figure 9
Stucco contacts patio.

Conflicting Regulations Result in Design and Construction Defects

One example of conflicting regulations is how the Americans With Disabilities Act (ADA) conflicts with the building code and results in a defect, as shown in **Figure 9**.

The ADA requires thresholds to be less than ¾ inches tall and even less in some cases. The typical condominium building threshold is designed for the ADA requirements. Expectably, a door frame will extend down to the threshold and floor. This results in what is shown in **Figure 9** — the bottom edge of stucco walls in contact with the paved patio floor surfaces (to support the door frame), which is contrary to the building code that requires 2 inches of clearance between the bottom of the stucco and paved surfaces. A forensic engineer, evaluating a building for construction defects, could conclude that because the stucco is in contact with the paved patio surface this is a construction defect caused by the builder. This would be an erroneous conclusion because the wall was constructed as it was designed. **Figure 10** shows the design of the exterior walls and patio material interface.

Figure 11 shows the code-required distance between the stucco and the patio, which is not possible unless a system of flashing was designed to cover the bottom plates and the bottom edge of the sheathing — something that would not be acceptable because the threshold elevation would have to be raised to allow continuous integration of the wall flashing with a threshold door pan flashing assembly to ensure the threshold would not leak.

The "solution" is to raise the door threshold to the elevation of the top bottom plate and install a system of integrated door pan and wall flashing, but that would

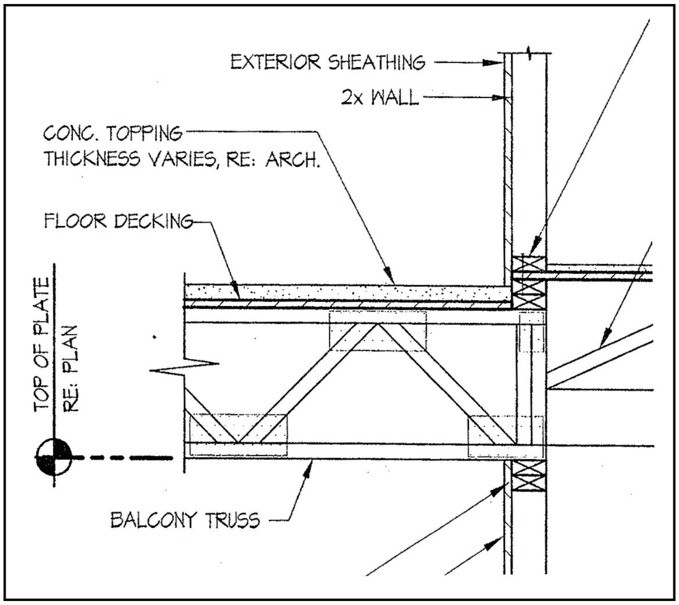


Figure 10
Wall/patio interface design.

Figure 12
Failing support walls.

violate the requirements of the ADA. Additionally, the author has found that many deem this detail aesthetically objectionable; therefore, some people would likely object to the aesthetics of a metal flashing band on their balconies.

Design Defects that Look Like Construction Defects

Figure 12 is an example of what was first thought by building owners to be a construction defect, but subsequent investigation and analysis determined the failure was caused by a structural engineering design error.

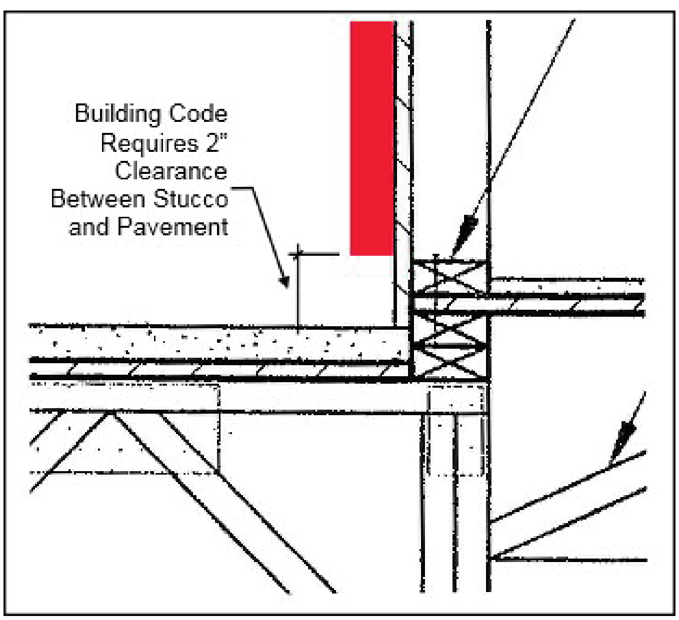


Figure 11
Stucco Code requirement.

The initial forensic engineering observations were of a failing structure that appeared to be collapsing in certain areas. The first possible cause investigated was whether underground utilities in the area were leaking and causing this failure. When an in-depth evaluation of the utilities was performed (using in-line cameras and other location equipment as part of the forensic analysis), the conclusion was that there were no utility leaks causing erosion or failure of the soil around the building.

The next phase of the forensic evaluation was to interview the structural engineer who was honest and admitted that the failure shown in **Figure 12** was a design mistake because the backfilled soil around the building had insufficient strength for the load imposed by the bricks, concrete blocks, and supporting concrete footings. The conclusion of the structural engineer was that to prevent future collapse — and to stabilize the perimeter of the building — helical piers needed to be installed to provide sufficient supporting strength for the footings, concrete blocks, and brick veneer on the four-story building.

Figure 13 shows another design error that was discovered in addition to the failure shown in **Figure 12**. **Figure 13** shows one of the numerous headers that were supporting open spans between the concrete block columns around the perimeter of the building. Other fractures observed at the corners required forensic evaluation

Figure 13
Over-spanned headers.

to determine the cause. The structural engineer reviewed the calculations with the forensic engineer and concluded that the headers were over-spanned for the capacity of the built-up steel header members, proving that this was a design error, not the responsibility of the builder.

Figure 14 shows a combined design and construction error. The over-spanned header shown in **Figure 13** that was incorrectly designed by the structural engineer was also mistakenly cut by the contractor, which resulted in the header improperly bearing a sharp edge rather than the entire width of the member. The original design mistake and this construction error combined to create a design

Figure 14
Incorrectly cut header.

Figure 15
Floor damage.

and construction defect; however, the over-spanned condition caused by the design mistake was the controlling defect because the bearing issue had not caused damage.

Material Failures that Look Like Construction Defects

Figure 15 shows what appears to be damage to a wood floor and door jamb from a leaking threshold and possible construction defect. **Figure 16** shows the wall base flashing just outside of the door is a deteriorated mess of rusted metal.

The initial hypothesis could be that this is a construction defect, but further investigation resulted in a different

Figure 16
Rusted flashing.

Figure 17
Rusted flashing.

conclusion. The owner of this condominium unit had an extensive collection of large potted plants and citrus trees on the patio that was serviced by a drip watering system, which resulted in a chronically wet patio. Additionally, the floor drain (located about 4 feet from this wall) was at a higher elevation, so water was not directed away from the flashing. Steel flashing is galvanized when it is manufactured, but when it is cut during fabrication, the exposed edges are no longer as corrosion resistant as the surface. Normal industry standards are to install metal flashing without corrosion-protective measures on the edges. The solution to this problem was to use lead-coated copper flashing with soldered seams, which are more corrosion resistant than cut galvanized sheet metal. Lead-coated copper was not specified by the designer either because the designer was not aware of it or because it cost more money than the developer wanted to spend. Economics, the designer, the developer, the contractor, and the material provider all had a role in choosing the flashing material that failed.

Figure 18
Observed "defect."

Figure 17 shows a situation that was observed throughout a 28-building condominium near the beach. This was a disappointing situation for the condominium owners because the condominiums were only about six years old when this evaluation was performed. A cursory visual inspection could lead to the preliminary conclusion that either the wrong flashing material was specified by the designer or the builder failed to use the correct material. Metallurgical evaluation of flashing material that was not rusted showed the galvanizing code for seaward properties, which requires heavier galvanizing than what is used in buildings located away from the beach. In this case, the correct flashing was specified by the designer, but the builder ordered the wrong material.

Post Construction Changes Can Appear to Be Construction Defects

Figure 18 illustrates what a forensic engineer identified as a failure to grade this side of the building with a swale for proper drainage as required by the code. That engineer concluded that the contractor or developer failed to meet the standard of care because the configuration of this side of the property did not meet the building code requirements for slope and drainage. In fact, the engineer surveyed elevations near the neighboring structure on top of pavers installed after construction and used that as "evidence" to suggest the contractor or developer caused defective drainage on this side of the building.

One of the important elements of a forensic evaluation the engineer failed to perform was to investigate the history of the condominium project before making definitive conclusion that the builder or developer failed to meet the standard of care. **Figure 19** is a photograph that was taken during construction, showing clear evidence that over time, site conditions (and related drainage) had changed between the buildings; the photo shows no bamboo was growing during construction and that there was a

Figure 19
Different site condition.

fence between the properties.

Reviewing construction photographs and researching the building inspection documentation (which showed the original drainage configuration was code-compliant and approved by the city) were basic forensic engineering evaluation steps that should have been taken prior to reaching final conclusions. Had the engineer performed this diligent analysis, he should have reached the conclusion that the site had been changed materially during the eight years since construction — and that the builder and developer had no responsibility for the changes.

Conclusion

The following elements should be considered when performing forensic engineering evaluation of buildings to provide a realistic, detailed, and fair evaluation of building performance issues, design-related elements, material failures, post-construction changes, and construction defects caused by the builder.

- Building performance is affected by numerous participants in the design, procurement, and construction process that can contribute to a constructed defect — not just the builder.
- Forensic engineering analysis of building performance issues requires more evaluation than just observing the current condition of so-called “construction deficiencies” because the current condition can appear to be builder-caused construction defects when they were caused by other issues or project participants.
- Conditions that appear to be defects can include code and ordinance conflicts, such as the ADA conflict shown in **Figures 9, 10,** and **11**, product and material failures, adverse or abnormal weather conditions, post-construction changes, lack of maintenance, abuse, and neglect.
- The forensic engineer must evaluate the available design documents, the building code, and other regulatory requirements to understand how those elements affect the building’s performance.
- When feasible, the forensic engineer should also evaluate project records, photographs taken during construction, maintenance records, performance complaints, owner interviews, engineer interviews, material specifications, submittals, shop drawings and other pertinent information that can provide more insight than the limited understanding provided by current observable conditions.

It is generally understood that the duty of forensic engineers is to serve the public interest by practicing their ethical and professional functions in a thorough and disciplined manner that reflects reality, honesty, independence, and a commitment to do what is right. They have a duty to the client, and they are neither the engineer of record, nor the triers of fact. Instead, they are generally retained not to make improvements to the building but to render opinions on causation and possibly liability. This duty means that observations of current conditions must be coupled with detailed evaluation of all available relevant information to fairly assign responsibility for building defect issues.

Forensic Engineering Evaluation of an Allegedly Deficient Steam Turbine Foundation

By Dhirendra S. "Sax" Saxena, PE (NAFE 586F)

Abstract

Forensic engineering as applicable to "construction materials evaluation" was used to investigate a condition where an alleged severe deficiency occurred during placement of concrete for a steam turbine generator (STG) structure in west central Florida. The owner questioned the integrity of the partially completed structure, and demanded removal/replacement of the structure. The author conducted a forensic investigation to determine whether the deficiency was limited to the surface, or if removal and replacement of the structure was warranted.

Keywords

Forensic engineering, concrete placement, honeycombing, corehole videography

Introduction

A forensic materials engineer is normally called upon to determine and evaluate the extent of damage to or deficiency of materials as well as to recommend corrective measures. In such investigations, the goal is generally understood early, as some type of known or suspected material performance has been reported that initiated the necessity for the investigation. Generally, the inspector and/or the forensic field professional collects data to better understand the most likely cause of the issue at hand.

Within civil engineering, qualitative procedures are used in practice areas ranging from geotechnical to materials engineering. Forensic engineering can involve an investigative program of materials, products, structures, or components that may have failed or do not operate or function as intended, thereby causing damage to property or triggering a questionable result.

During the construction of an STG structure within a powerplant complex in west central Florida, an alleged severe deficiency was asserted regarding concrete structures. A significant amount of concrete was cast into a total of eight structural columns with interconnecting overhead beams. Upon removal of the forms, a visual inspection revealed an objectionable condition in the form of concrete honeycombing, segregated aggregate, voids, and rock pockets. It was observed in a major portion of the 20-ft structure's height in most of the columns and beams, and appeared more severe in the lower, 8- to 12-ft, zone. Likely factors contributing to this condition ranged from exceeding the specified lift of deposited layer thickness during concrete placement to inadequate consolidation of placed concrete. **Figures 1** and **2** illustrate these conditions.

The project owner raised questions regarding the structural integrity and possible need for replacement/removal of this partially completed STG structure. The general contractor agreed to undertake a detailed investigation program to determine whether deficiency was limited to the surface. Additionally, this process would determine if the extent of any deficiency could be

Figure 1
Close-up showing honeycombing and segregation of concrete.

Dhirendra S. "Sax" Saxena, 4175 South Pipkin Rd., Suite 106, Lakeland, FL 33811; (863) 226-0612 (x 215); dsaxena@billerreinhart.com

Figure 2
Voids and rock pockets being cleaned by hydro-blasting.

addressed by repairing the voided areas or if removal of the structure was, in fact, necessary. Failure, or alleged failure, was defined by the project owner as an unacceptable difference between expected and observed performance. A three-stage investigative program, consisting of an internal/external condition survey, a field investigation and laboratory evaluation, and a remediation/restoration program, was undertaken.

Stage 1 Investigation

Stage 1 consisted of a pre-remediation survey (PreRS), encompassing an external and internal condition assessment.

<u>Condition assessment — external</u>

The first phase of the PreRS consisted of visually inspecting, logging, photographing, and documenting each of the eight columns to evaluate the deficiency at the surface and to detail the depth of voiding and honeycombing. The column located in the far northeast portion of the STG structure showed extensive honeycombing across the base. In addition, the underside of the crossbeam in the northwest portion of the STG structure, spanning between the two columns, showed honeycombing, segregation, and voiding.

<u>Condition assessment — internal</u>

The second phase of PreRS was carried out through a field program that consisted of the following elements.

Field coring and laboratory evaluation program. Part one of the internal condition assessment consisted of coring horizontally at 22 strategic locations (bottom, middle, and top sections of columns and one overhead beam spanning between columns). The entire field coring program consisted of the retrieval of a series of 2.75-in.-diameter cores from each corehole in 1-ft sections cored along the horizontal and vertical directions. A total of four or five core runs were retrieved from each horizontal corehole. In view of the very close spacing of steel rebars within the columns, the investigative forensic consultant decided to limit the core size to 2.75-in.- diameter. This was done to avoid any conflict with the existing steel during the coring operation.

A total of 66 cores were retrieved, sawed, trimmed, capped, and cured. Following adequate curing, these cores were subjected to compressive strength tests, which reported a 28-day average comprehensive strength of 4,960 psi.

Part two of the internal condition assessment consisted of petrographic examination of hardened concrete cores as per applicable standards (ASTM C865-14). These 2.75-in.-diameter cores were examined using a petrographic microscope to determine their integrity, quality, and constituents. The petrographic examination showed the paste/aggregate quality ratio, bonding characteristics, and any void system in the paste. It revealed the quality of the concrete to be adequately dense and bonding to be intact in major portions of the core with the exception of the surface where honeycombing was apparent. In general, the paste/aggregate ratio ranged from 35/65 to 60/40 with the average being 50/50. The water-cement ratio was interpreted to be 0.45 to 0.50 and was found to be acceptable and within the designed specification. Small spherical voids, typical of entrained air, were also noted to be present in the concrete. The concrete, which appeared to be adequately consolidated outside the noted voided areas, exhibited no evidence of detrimental internal paste-aggregate reaction.

TV video examination. Part three of the internal condition assessment consisted of a video examination of the interior surfaces of each corehole to confirm the concrete quality and identify any nonconforming features of paste/aggregate. This corehole camera survey was carried out utilizing a 1.5-in.-diameter Reese corehole video camera. It was equipped with a 90° side-viewing lens capable of rotating 360° and having a 7X magnification.

A detailed and thorough visual examination of the concrete in the interior portion(s) of all eight columns was performed by the petrographer. As the camera moved slowly through each of the coreholes, the petrographer

Figure 3
Insertion of the video camera through corehole near column base.

Figure 4
Petrographer examining the video screen for internal soundness.

documented and evaluated any unusual characteristic within the concrete as is illustrated in **Figures 3** and **4**. All the 22 core locations were examined to complete the internal condition assessment.

Packer tests. Part four of the internal condition assessment consisted of performance of Packer tests at six strategic locations. These locations were cored, and the cores were removed. The purpose of these Packer tests was to determine competency of in-place concrete as related to internal voids or large honeycombing that was not visible from the exterior and that might affect the structural soundness.

The Packer test was performed by sealing one or both ends of the cored hole into or through the structure and forcing water pressure into the core hole. Water was forced through a device comprised of a water meter capable of reading to 1/100th of a gallon and a pressure gauge capable of reading the pressure build-up with a shut off valve to close off and maintain pressure.

The pressure testing for this project consisted of forcing water under pressure through the device using the on-site water pressure, allowing the valve to remain open with a constant pressure of 30 to 50 psi and measuring the amount of water, if any, required to maintain the pressure in the cored hole at the maximum pressure achieved. Based upon a thorough evaluation of the Packer tests data, it was concluded by the forensic consultant that the internal concrete was competent. The STG structure layout identifying columns, overhead beams, core TV video, and Packer test locations is shown in **Figure 5**.

Stage 1: Conclusions and Remarks

The Stage 1 forensic investigation, consisting of a visual, video, and petrographic examination as well as results of compressive strength tests performed on cores revealed that:

- Structural soundness and competency of the concrete in the eight columns and interconnecting beams was substantially intact;

- The columns, as evaluated consisted of satisfactory quality concrete and retained the mass and integrity for which they were intended;

- The exterior honeycombing, segregation, and voiding, which in many cases exposed the rebar, was determined to be limited to the surface; and,

- Development and implementation of a restoration program was recommended to repair the external honeycombing and voiding, following removal of all loose and non-intact paste and aggregate from the affected areas by hydroblasting.

Therefore, it was concluded, recommended, and agreed upon by project team members that an extensive restoration was feasible and should be pursued as an acceptable and economic alternative.

Stage 2: Remediation/Restoration

Based on the findings and recommendations from the Stage 1 investigation, the retained consultant developed a remediation and restoration program to rehabilitate the STG structure to its originally intended design. This

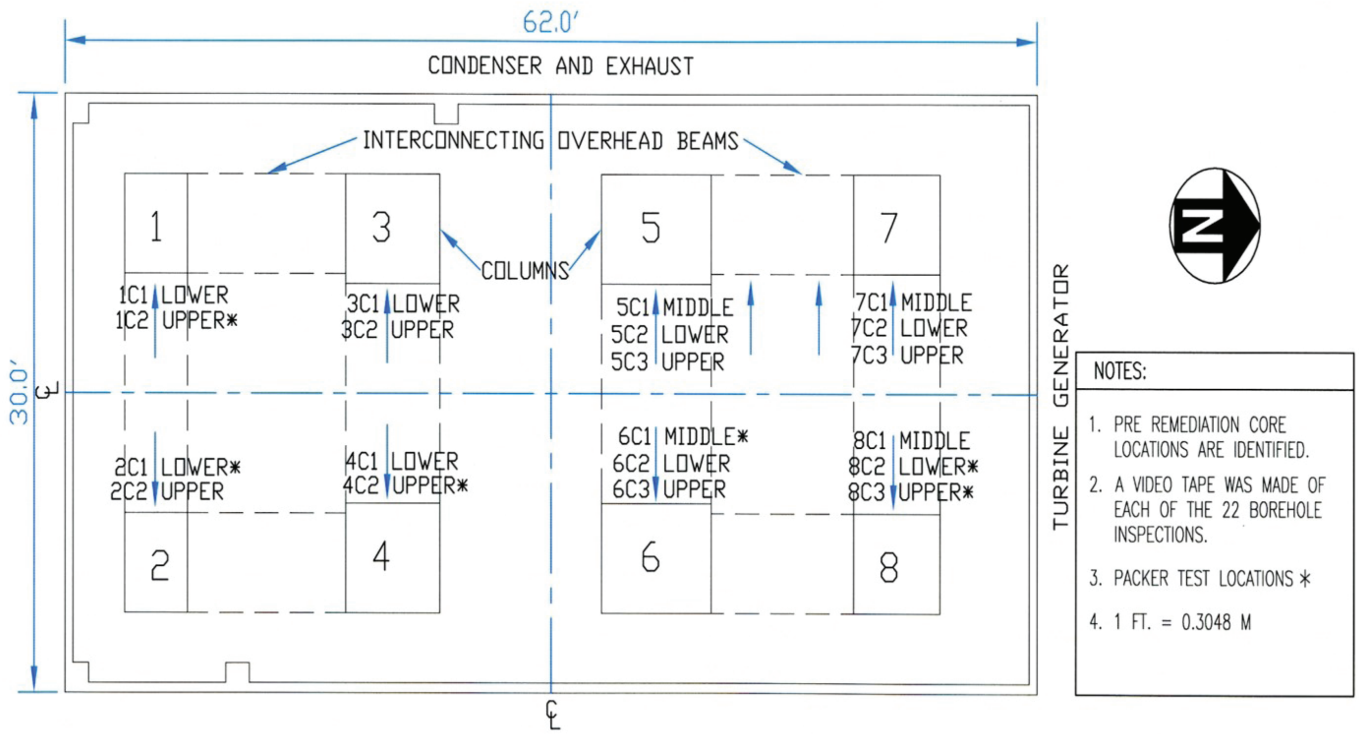


Figure 5
STG structure layout identifying columns, overhead beams, core, and Packer test locations.

remediation and restoration program consisted of:

1. Preparation of guideline specifications as well as a remediation and restoration program;

2. Chipping and hydroblasting of honeycombed and void areas;

3. Spraying or coating hydroblasted and dried surface using an acceptable bonding agent to create a bonding badge;

4. Forming, pumping, and pouring a high-strength grout mixture;

5. Pumping the grout from the bottom to ensure proper bonding and complete filling of externally accessible honeycombed, segregated, and voided areas;

6. Hand-troweling and packing into cored holes to ensure complete filling; and,

7. Reviewing proposals from various specialty subcontractors for the remediation and restoration program that would effectively restore voided areas as well as the surficial honeycombing.

During the entire Stage 2 restoration program, the retained consultant provided monitoring and inspection services for various operations including quality of the grout, forming, and the application procedures. Any defects in workmanship or grouting quality were immediately noted and corrected by the specialty subcontractor. Some overhead beam areas were determined to be lacking in bond as determined by visual separation in core specimens. These areas revealed insufficient bonding, and the specialty subcontractor was directed to chip the grout out for inspection and re-perform the repairs. A typical photograph showing sections of a pre- and postremediated column is shown in **Figure 6**.

Stage 3: Post-Remediation Survey

The purpose of the Stage 3 post-remediation survey (PostRS) was to assure integrity and competency of the restored concrete columns and interconnecting overhead beams in the STG structure. The scope of work included:

1. A detailed visual inspection of the chipped and hydroblasted portions of the honeycombed and voided areas and a selection of a number of areas for coring;

2. Surveying repaired/restored areas;

Figure 6
View of exposed column with pre- and post-restoration areas.

Figure 7
Tensile test set-up.

3. Evaluation of the performance of the remediation program by recovering and testing cores drilled through repaired grout materials and original concrete of each of the columns at 14 locations;

4. Performing microscopic examination and evaluating the bonding characteristics of the original and grouted surface by conducting tensile strength tests.

The initial phase of the PostRS consisted of coring horizontally a total of 14 cores through the repaired grout/concrete bond in the upper and lower sections of each of the columns. These 2.75-in-diameter cores were removed and examined by petrographic analysis using microscopic examination. The microscopic examination of the concrete revealed the quality of the concrete to be excellent and bonding characteristics to be intact in a statistically significant portion of the cores.

A total of 14 core specimens were sawed, trimmed, capped, and cured. Following completion of curing, three core specimens were subjected to compressive strength and direct tensile strength tests at seven- and 28-day time intervals after restoration. The compressive strength average for the 14 core specimens at 28 days was 5,800 psi.

The core specimens were subjected to direct tensile strength tests (ASTM C496) and exhibited failure within the original concrete with the failure mode to be through paste and aggregate as illustrated in **Figures 7** and **8**. In addition, the average direct tensile strength values of the core specimens in remediated or restored areas compared favorably (i.e., equal or greater) with that of the original concrete core specimens. Failure characteristics were noted to be normal.

The STG structure layout showing areas exhibiting deficiencies and requiring remediation as well as the PostRS core locations is shown in **Figure 9**.

Concluding Remarks

- Following completion of the Stage 2 remediation/restoration — and based upon results of Stage 3 post-remediation survey and a thorough review of the remediation details — it was determined by the project owner that the repair of eight columns and associated overhead beams had been achieved satisfactorily.

- The final repair resulted in restoration of the STG structure to its originally planned and designed dimensions and design conditions, as depicted in **Figure 10**.

Figure 8
Tensile strength tested core.

- Application of forensic engineering principles was a key factor in restoration of the STG structure.

- Following satisfactory completion of the remediation program, the retained forensic consultant recommended acceptance of the restored structure to the client.

Figure 10
View of repaired STG structure.

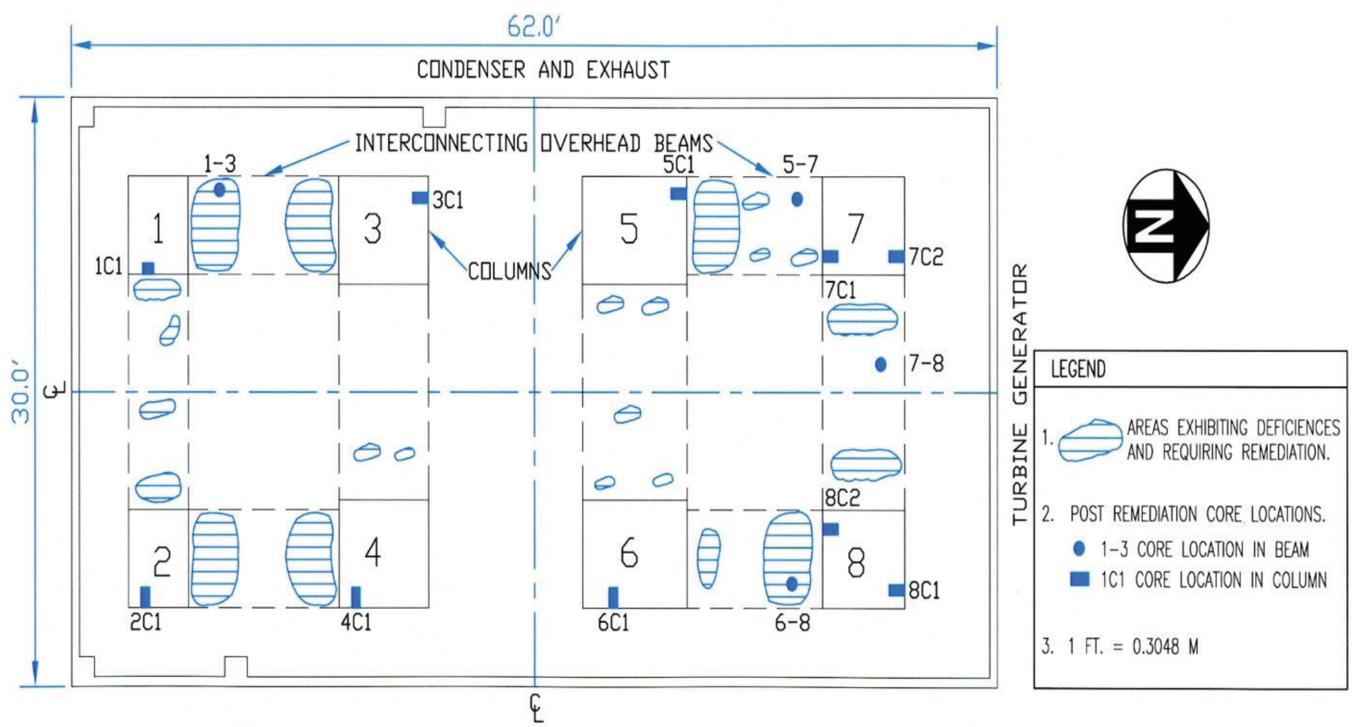


Figure 9
STG structure layout showing deficient areas and post-remediation core areas.

- A view of the restored structure is illustrated in **Figure 10**.

Acknowledgements

The opportunity to perform the services described herein provided an interesting exercise in the planning and execution of this unique project. The information herein is from a project where the author was involved as the forensic engineering and material testing consultant. It must be stated that the remediated and restored STG structure has been in operation for the last 20 years to the client's and owner's satisfaction. The author expresses his appreciation to the other project team members, including the general contractor, specialty restoration sub-contractor, and the petrography consultant.

Bibliography

ASTM C865-2014. Standard practice for petrographic examination of hardened concrete. West Conshohocken, PA; ASTM International.

ASTM C496-2017. Standard test method for splitting tensile strength of cylindrical concrete specimens. West Conshohocken, PA; ASTM International.

Forensic Engineering Analysis of a Motorsports Racing Incident

By Stephen D. Knapp, PE (NAFE 891S), Richard M. Ziernicki, PhD, PE (NAFE 308F), and Ben T. Railsback, PE (NAFE 713S)

Abstract

The motorsports racing industry was built on the foundation of people wanting to engage in competition, take risks, and enjoy the capabilities of their go-fast hobbies. Risk undoubtedly accompanies such dangerous activities. As a result, race participants sign a waiver, giving up their right to file claims against organizers of the racing event. Who then is liable for the failure of a component that is certified for racing and is responsible for an injury? This paper will address this question and outline important factors related to an incident involving the failure of a race-certified transmission flexplate that resulted in serious injury.

Keywords

Forensic engineering, racing, standards, failure analysis, certified, certification, flexplate, SFI

Case Study

In July of 2011, a drag racer of a modified pickup truck was racing his vehicle at a local National Hot Rod Association (NHRA)[1] event. Prior to starting the race, the driver was performing a burnout — a procedure where the subject vehicle remains stationary while spinning the vehicle's driven wheels to heat the tires for racing. During the burnout, it was reported that an object came free from the pickup and struck a crew member, causing serious injury. It was later determined that a transmission flexplate counterweight had separated from the vehicle and was found the next day by a track official in the vicinity of the incident. In addition, the racer of the vehicle was able to verify that he had lost the counterweight from the vehicle's flexplate. The racer indicated he had purchased the flexplate only months before the incident, prior to the start of racing season.

Product Discussion

On a vehicle equipped with an automatic transmission, a flexplate is attached between the engine crankshaft and the transmission's torque convertor. A flexplate is similar to a flywheel in a manual transmission engine; it provides a mechanical coupling between the engine's crankshaft and transmission. Depending on the type of engine, some flexplates will have a balance weight attached to them to achieve proper engine rotational balance. During the subject incident, the counterweight separated from the rotating flexplate and exited through an access port located on the bottom of the bellhousing. At the time of the separation, the counterweight had a tangential velocity of approximately 160 mph. The counterweight struck a crew member who was standing beside the vehicle in a restricted area of the race track.

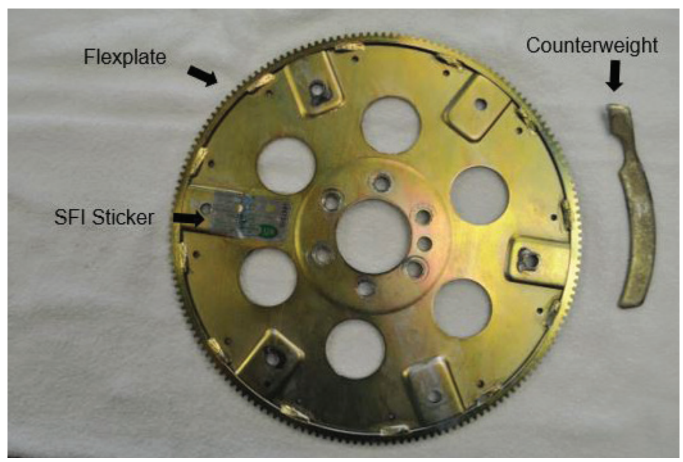


Figure 1
Subject flexplate with separated counterweight.

The subject flexplate (**Figure 1**) includes a stamped steel inner disc with the ring gear and counterweight welded to the inner disc. It was manufactured to work with an externally balanced Chevrolet-based 454 Cubic Inch Displacement (CID) engine. The flexplate was labeled with a SEMA Foundation Inc. (SFI)[2] 29.1 certification sticker.

Stephen D. Knapp, PE, Richard M. Ziernicki, PhD, PE, and Ben T. Railsback, PE, 7185 South Tucson Way, Englewood, CO 80112-3987, 303-925-1900; sknapp@knottlab.com, rziernicki@knottlab.com.

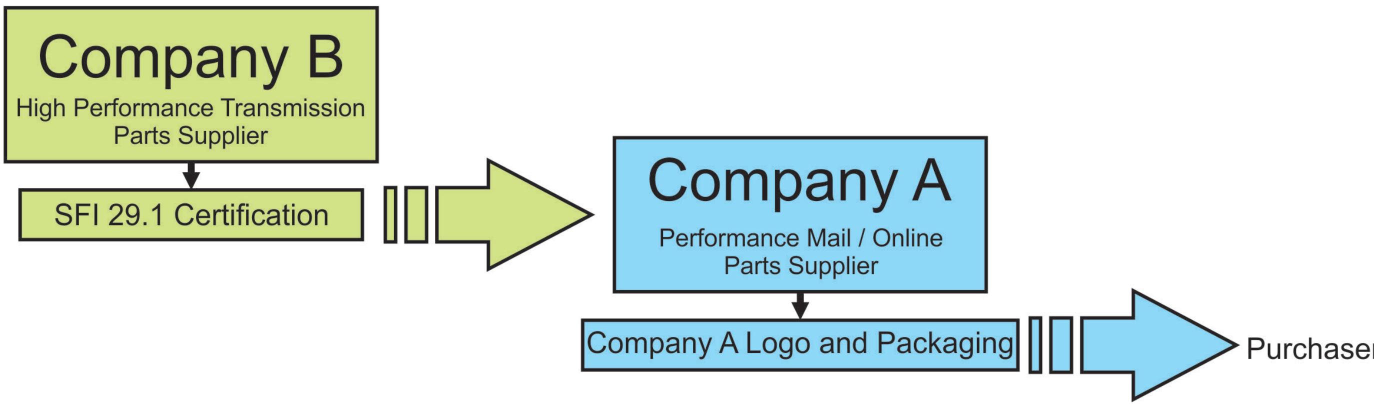


Figure 2
Company A original business model.

SFI 29.1 Overview

The SFI Foundation specification 29.1 "establishes the uniform test procedures and minimum standards for evaluating and determining performance capabilities for Automatic Transmission Flexplates used by individuals engaged in competitive motorsports[3]." During SFI 29.1 testing, the flexplates are spin tested between 12,500 and 13,500 rpm for a duration of one hour, then examined for signs of failure, such as cracks, fractures, weld failures, etc. Upon completion of the spin test, the flexplate is destructively sectioned and cut into metallurgical samples to analyze and test for the minimum yield strength, minimum tensile strength, and percent elongation of the material. These mechanical properties are compared to minimum standards set forth by SFI 29.1. SFI further states, "…logo/designation is in no way an endorsement of certification of product performance or reliability by SFI."

Representative Sample Testing

SFI 29.1 requires a manufacturer to test a single representative product unit every two years. According to SFI: "For a given model, the largest outside diameter with the smallest crankshaft mounting bolt pattern shall be selected[4]." SFI also states: "If all other factors remain the same, a dimensional change in outside diameter or mounting bolt pattern is not considered a model change[5]." Therefore, the SFI certification process does not require testing of individual model flexplates for various different engine configurations — only a representative sample meeting SFI's specific criteria for testing is required. In addition, testing of a flexplate unit without a counterweight (zero balanced) was acceptable to SFI as meeting the criteria necessary to be considered a representative sample.

National Hot Rod Association Rules

The subject incident occurred during an NHRA drag racing event. For a driver and vehicle to be qualified to race in a drag racing event, the driver, necessary safety gear, and vehicle must comply with the rules set forth by the current NHRA Rulebook. With drag racing being an Elapsed Time (ET) event, the rules and regulations set forth by NHRA are based on a vehicle's ET as well as the achieved speed of the vehicle in miles per hour (mph). The quicker and faster a vehicle becomes, the more safety regulations a racer and vehicle will be required to comply with. Many of the NHRA rules specify the use of equipment that complies with SFI specifications. For racers having an ET quicker than 10 seconds in the quarter mile — or faster than 135 mph — a flexplate complying with SFI 29.1 certification becomes required according to NHRA rules. Because the subject race vehicle was slower than 10 seconds ET (had an ET higher than 9.99 seconds), SFI 29.1 flexplate certification was not required on his vehicle.

Manufacturing / Reselling Process

The subject flexplate was purchased by the racer from an online/mail-order high-performance parts distributor (Company A). The heavy-duty flexplates sold by Company A were originally supplied in bulk from a performance transmission parts distributor (Company B) and came complete with an SFI certification sticker. After being received by Company A, the part was packaged with the logo of Company A and put into inventory for sale. A flow chart showing the original business model established by Company A is shown in **Figure 2**.

Later, the business model changed when Company B decided to quit supplying Company A with its flexplates. As a courtesy to Company A, Company B divulged that it had not been manufacturing these parts themselves but rather obtaining these parts from a parts supplier (Company C) and that Company A could continue to be supplied with flexplates from Company C. Company C was willing

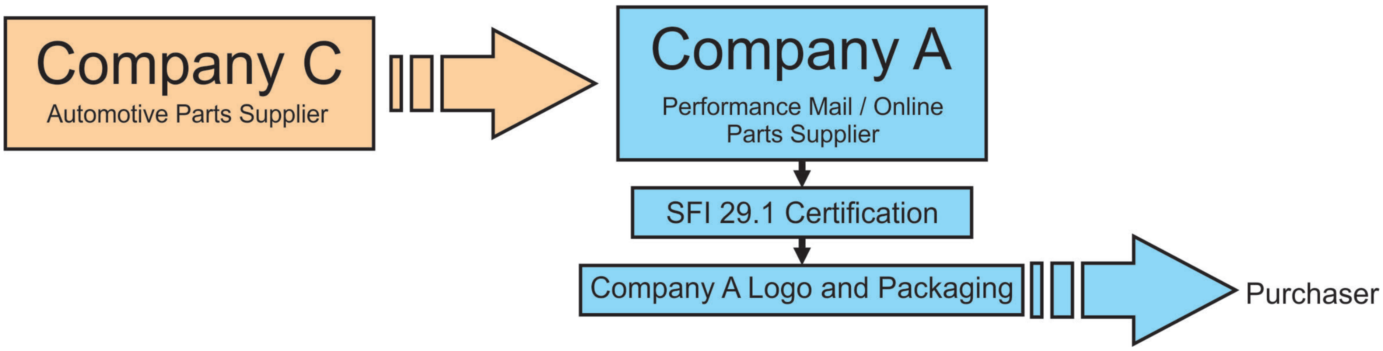


Figure 3
Company A modified business model.

to continue to sell flexplates to Company A, provided that Company A perform its own SFI testing and certification process on the flexplates. To accomplish this, Company A consulted directly with SFI and its test lab to comply with the necessary SFI testing protocols required to continue selling the flexplates as SFI certified. The business model known to Company A at the time of the subject flexplate sale is shown in **Figure 3**.

After the subject incident (and all parties were put on notice), it was discovered that the actual manufacturer of the part was a fourth entity (Company D), which sold its product as a heavy-duty flexplate to Company C. This company contended that the part it manufactured was never intended for the high-performance market. The flow chart of the actual business model that was in place at the time the subject flexplate was sold is shown in **Figure 4**.

Company D reportedly manufactured the subject flexplate and used an automatic wire Metal Inert Gas (MIG) welding machine to weld the ring gear to the inner disc. The counterweights were MIG welded to the flexplate inner disc by hand (manually), rather than using an automated process like the ring gear connection to the disc. As observed in **Figure 1**, the counterweight is detached from the flexplate assembly. Three welds were observed on the subject flexplate steel inner disc in areas that were intended to join the counterweight to the flexplate assembly. However, the welds between the flexplate inner disc and counterweight did not fully join and penetrate the counterweight during the welding process. The lack of weld penetration is clearly visible, as shown in **Figure 5**. It can be seen that between the arrows there is no significant melting consistent with the counterweight having been joined with the flexplate inner disc as a result of the welding process. The lack of penetration, melting, and joining of the two parts is a welding defect known as a "cold weld." Because the product is coated with a gold-colored anti-corrosion material (zinc dichromate) after welding, certain welding defects, cracks, or disparities would not be visible to those handling the product after it was manufactured by Company D and prior to the counterweight separation.

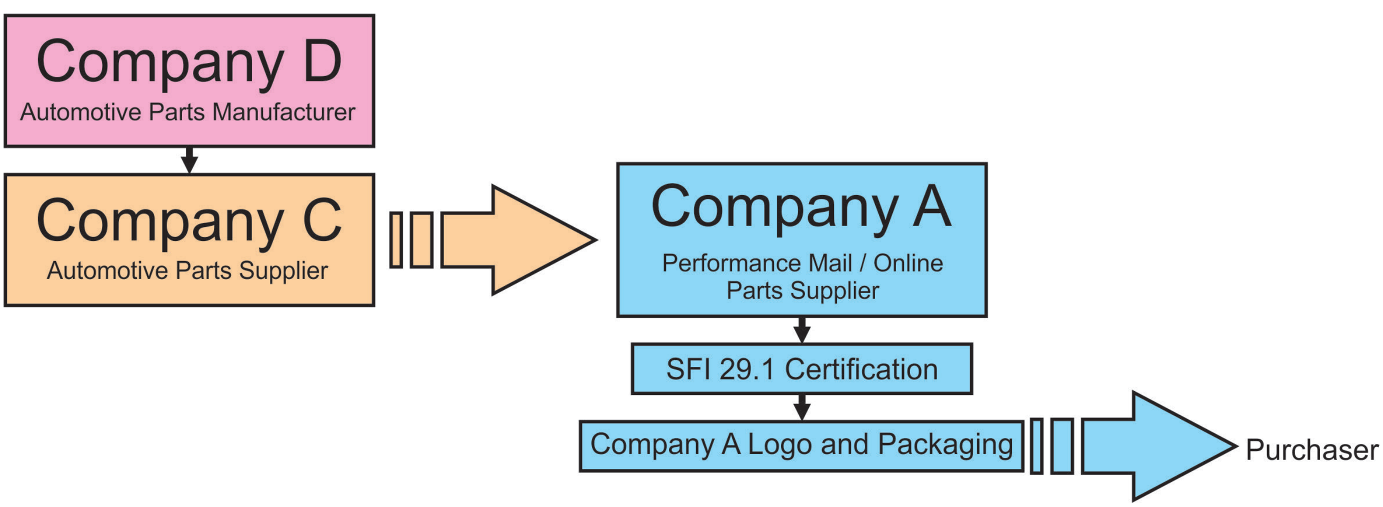


Figure 4
Actual business model at the time of the product sale.

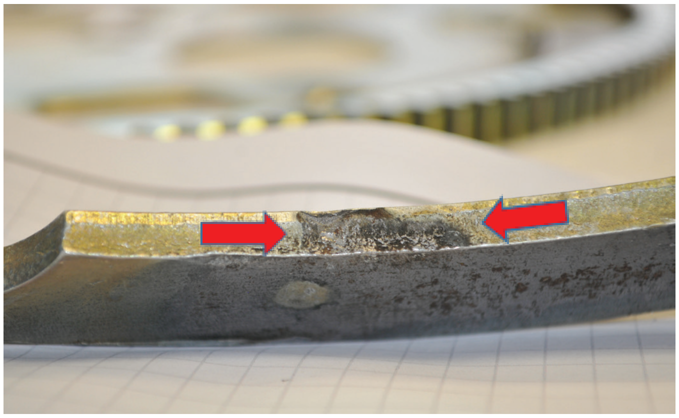


Figure 5
Lack of weld penetration.

Metallurgical analysis consisting of Scanning Electron Microscopy (SEM), sectioning of the counterweight, and metallography further confirmed the lack of weld penetration to the counterweight during the assembly of the flexplate. Metallurgical properties consistent with the machine blank formation of the part were also visible in the area where the weld was attempted. During the stamping process, the counterweight is machine stamped from a sheet of metal under extreme mechanical pressure using a custom die. The pressure initially cuts the materials, but as the process progresses, the remaining stock separates from the stamped sheet metal as a result of high shear forces.

This shearing process creates two very distinct patterns on the edge of the counterweight, as shown in **Figure 6**. The portion of the part that is cut by the die has a clean and smooth edge as highlighted in red text in **Figure 6**. The portion that shears and separates from the stock material has a rough and unfinished surface, as highlighted in blue in **Figure 6**. These characteristics run the length of the edge of the counterweight. Melting of the material due to weld penetration would eliminate these surface characteristics during a proper welding process. However, it can be seen in **Figure 6** that these surface characteristics remain in the area that the counterweight was intended to be welded, and confirms that it lacks weld penetration. Further, the gold coating that is applied after the welding process is visible on the surface of the weld circled in blue in **Figure 6**, indicating that the materials were not joined at the time of the gold coating application.

Figure 6
Failed counterweight and weld — blue area indicates shear region; the red area indicates area cut by die; the gold coating found on the weld bead surface is circled in blue.

Discovery documents indicated that the Company D "heavy-duty" flexplates were supposed to be manufactured with additional welds as its sales literature indicated: "Balancing weights are not only resistance welded but are also MIG welded for better holding power of these weights." However, based on visual examination of the subject counterweight, the process of joining the counterweight to the flexplate with resistance welding was omitted on the subject flexplate.

Company D reported that it did not perform testing of flexplates according to the SFI 29.1 Quality Assurance Specification. In fact, Company D stamped "NON SFI" on the flexplate. Company D also reported that it omitted complying with any industry standards related to the rotational speed capability of its flexplates. Society of Automotive Engineers (SAE) Standard J1456[6] for "Maximum Allowable Rotational Speed for Internal Combustion Engine Flywheels" and SAE Standard J1240[7] "Flywheel Spin Test Procedure" are two automotive industry standards that relate to the quality and capability of flexplates. Under the SAE J1456 standard, a rotational test speed of 13,750 rpm would be required of a Chevrolet 454 engine with a factory maximum recommended rotational speed of 5,500 rpm.

SFI 29.1 Spin Testing of Exemplar Externally Balanced Flexplates

Spin testing was performed with exemplar flexplates using the test requirements of SFI 29.1 and the test configuration as recommended by SAE J1240. The testing was conducted with two exemplar externally balanced flexplates at a spin testing laboratory. Unlike the subject flexplate, the available stock of exemplar flexplate assemblies had counterweights that were both MIG welded and resistance welded to the flexplate assembly. The addition of the resistance welds was a change that was apparently implemented after the subject incident for additional securement of the counterweight. To conduct the test, the

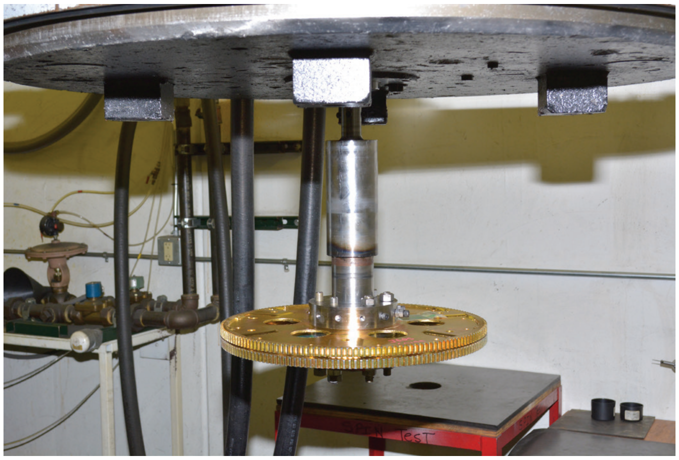


Figure 7
Testing of exemplar externally balanced flexplates.

two exemplar flexplate assemblies were coupled together with a test fixture having their counterweights opposite of each other to make a balanced assembly (**Figure 7**). Spin testing of the exemplar flexplates was conducted above 12,500 rpm for one hour in accordance with SFI 29.1 without failure to either of the flexplate assemblies or attachments of the counterweights.

SFI 29.1 Testing is Destructive

The SFI 29.1 testing protocol is destructive, preventing the tested product from being put into service after testing. Upon completion of the spin testing, the flexplate is cut into sections in order to test the mechanical properties of the flexplate material. This process destroys the flexplate, preventing it from being put into service. Therefore, any individual flexplate having SFI 29.1 certification has not undergone SFI 29.1 testing itself.

Evaluation of Exemplar SFI Certified Flexplates for Chevrolet 454 Engines

The authors examined 12 heavy-duty Chevrolet 454 externally balanced flexplates, each sold under a different brand name. The examination of these externally balanced SFI-approved flexplates shows that the subject flexplate was of virtually the same design and quality of those commercially available on the market. Examination of these flexplates shows that the common industry practice of securing the counterweight to the flexplate assembly is with five to six individual MIG welds encompassing the perimeter of the counterweight. This was different than the subject flexplate that used three relatively small MIG welds for securement of the counterweight, as shown in **Figure 8**. While stress analysis shows that the three welds would be adequate to secure the counterweight to the flexplate and even meet the requirements of SFI 29.1, the fewer number of welds increases the probability of a counterweight separation in the event of a defective weld.

SFI 29.1 Update

In August of 2016, SFI changed its protocol for testing flexplates that are equipped with counterweights. According to the new rules: "For a model to be certified with counterweights, it must be successfully tested with counterweights in place. The flexplate must be balanced by additional weights by the manufacturer before submitting the part for testing." With these changes, SFI has acknowledged that the securement of the flexplate counterweight is an important safety consideration and should be tested. However, as previously discussed, the testing requires a manufacturer to test only a single representative product every two years. Therefore, even with the new SFI protocols, defects in the securement of the counterweight would need to be monitored by the manufacturer on an individual basis to prevent a similar incident from occurring.

Conclusion

The root cause of the flexplate counterweight detachment was due to a manufacturing defect and failure to properly secure the subject counterweight to the flexplate at the time of assembly. The lack of weld penetration over a small effective weld perimeter allowed the counterweight to fail after minimal use.

Resistance welds that were a part of the original design for securement of the counterweight to the flexplate

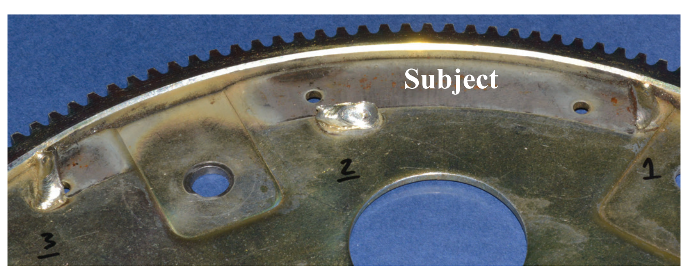


Figure 8
Comparison of the counterweight securement between an exemplar and the subject flywheel.

were omitted by the manufacturer on the subject product. Because the counterweight became detached and struck a crew member involved in the racing event, the manufacturing defect is also the cause of the subject incident. Due to the manufacturing process, which involves coating the flexplate after assembly, certain welding defects would not be visible to those handling the product after it was manufactured.

The manufacturer of the flexplate did not have an active quality control plan in place, and the defective weld went unnoticed until the subject accident. While the reseller of the flexplate completed and passed the SFI 29.1 certification process on a representative flexplates sample, it did not have involvement in the quality of each unit. In fact, SFI 29.1 certification is a destructive process, preventing the tested product from being put into service after testing. None of the companies related to the sale/resale of the subject flexplate had a role in quality control regarding the securement of the counterweight other than the original manufacturer of the part. However, because the reseller certified and placed its brand name on the product as if it was the manufacturer, it was held accountable for quality control even though these measures were outside of its control.

References

1. National Hot Rod Association (NHRA), Glendora, CA.
2. Specialty Equipment Market Association (SEMA), Diamond Bar, CA.
3. SFI Specification 29.1-2006. Quality Assurance Specifications: Automatic Transmission Flexplates. Diamond Bar, CA; SFI Foundation Inc.
4. Ibid.
5. Ibid.
6. SAE J1456-1984r1995. Maximum Allowable Rotational Speed for Internal Combustion Engine Flywheels. Warrendale, PA; Society of Automotive Engineers.
7. SAE J1240-1991. Flywheel Spin Test Procedure. Warrendale, PA; Society of Automotive Engineers.

Forensic Engineering Analysis of Quadcopter Drone Personal Injury

By Robert O. Peruzzi, PhD, PE (NAFE 954A)

Abstract

A hobbyist/owner was using her remote-control model quadcopter drone for the first time when it descended and collided with a bystander. The owner believed there was a malfunction. The retaining insurance adjuster requested a review of the owner's manual and user's guide, photos and diagrams of the scene, e-mail communications, police report, and a forensic investigation of the quadcopter to determine if there was a malfunction. This paper introduces unmanned aircraft systems (UASs) for hobbyists, describes the UAS involved in this incident, outlines the planned investigation steps, and describes the sequence of events of the incident as well as resolution of the investigation. The initial activity for this case (reading manuals) prompted a question to the owner, the answer to which exposed her lack of aircraft and operating knowledge. The author convinced her that continuing the case might be embarrassing as well as costly. The planned investigation was never executed.

Keywords

Forensic engineering, unmanned aircraft system, unmanned aerial vehicle, UAS, sUAS, UAV, sUAV, remote-controlled aircraft, hobbyist, quadcopter, drone, wireless remote control, safety

Introduction

The 21st century will, in many ways, be the century of the unmanned aircraft[1]. Drones are a hot item. Although some may consider drones weapons of war, a threat to personal privacy, a leap forward in video technology, or hazardous toys, they are much more useful than the confines of these limitations — and will soon affect our everyday lives in a host of ways[2].

The growing phenomenon of unmanned aerial vehicles (UAVs) for hobbyists began in 2008 with the Top Gun RC Airplane Contest[3]. Presently, sales of hobbyist and commercial unmanned aircraft systems (UASs) are predicted to increase from 2.7 million units in 2016 to 7 million units by 2020, as estimated by the FAA[1]. A more aggressive estimate, revealed in January 2016 from technology market intelligence firm ABI Research, predicts that UAS sales to the consumer market will surpass 90 million units and generate $4.6 billion in revenue by 2025[4].

UAS usage by hobbyists and commercial entities presents a risk to safety that is addressed by the Federal Aviation Administration (FAA). In 2012, the FAA enacted an exemption process for commercial use of drones in Section 333 of the FAA Modernization and Reform Act of 2012[5]. The FAA released its first regulations on hobbyist use of drones in "The Small UAS Rule," FAA sUAS Part 107 of June 2016[6]. For both hobbyist and commercial use of small UASs, maximum altitude is confined to 400 feet, and flight is constrained to be within the operator's line of site[1,5,6]. It is important for forensic engineers to note that forensic use of UASs are covered by Section 333, falling outside of the Part 107 rules for hobbyist drones.

New commercial applications are developing rapidly, despite local regulations being in a state of flux. Some new applications are package delivery, agricultural and safety inspections, industrial and consumer photography, humanitarian aid, first responder assistance, and surveillance[2].

There is much work left to do to keep the public safe as the UAS market continues to grow at a rapid rate[1]. UAS operators are required to register their aircraft with the FAA[2], and the UAS owner manual for the subject device strongly suggests obtaining training. Owner's manuals may spell out federal regulations and rules of safe operation, but there

Robert O. Peruzzi, PhD, PE, 719 Fourth Ave., Bethlehem, PA 18018, 610-462-3939; peruzzi@rperuzzi.com.

are no requirements for training or licenses for UAS hobbyists as of the date of this paper. Since there is no requirement to report hobbyist UAS crashes to any civil aviation authority, there are no reliable statistics on drone crashes. However, online searches for "quadcopter crashes" turn up multiple articles about injuries and property damage.

This paper reports an analysis of an injury due to a crash of a small (under 55 pounds[5]) UAS (sUAS) quadcopter drone operated by a novice hobbyist, who claimed an aircraft malfunction had taken place.

Background

Early one midsummer's evening with plenty of daylight remaining, under partly cloudy skies and mid-70s temperature (according to historical meteorological data collected approximately eight miles from the site of the incident), a novice owner of a new quadcopter drone took it to a city park for its maiden flight. She set it up on a playground basketball court, started it up, and caused it to lift off. Soon thereafter, she lost control of the aircraft, which flew away from the basketball court, through some trees, out of the park, and descended — striking an unsuspecting bystander. The operator and victim visited a nearby police outpost and reported the incident. Fortunately, the bystander reported no serious injuries. Nonetheless, the bystander later sued the owner/operator of the quadcopter drone.

The operator notified her insurance agent and retained an attorney, saying that the drone malfunctioned and "dropped onto the claimant." The insurance agent contracted with the author through an expert witness agency.

Small Unmanned Aircraft Systems for Hobbyists

Drones are essentially flying robots[7]. A "small" drone, weighing less than 55 pounds[5], is sometimes referred to as an sUAV. As one might guess, warfare was the earliest use of drones, dating back to air balloons carrying explosives in 1849[7]. Radio-controlled aircraft were used in World War II as aerial torpedoes and during the Cold War, both as target-drones and for data collection[7]. Earliest civilian and hobbyist UAVs were fixed-wing remote control aircraft[3]. Quadcopters, also called rotorcraft, appeared later and have become widely available to hobbyists since the early 2010s[7].

Quadcopters use two pairs of spinning rotors. Two rotors spin clockwise, and two rotors spin counter-clockwise. Computer algorithms translate joystick commands to adjust altitude, speed, or direction into wireless signals that control the rotor spin rates. The combination of four rotor spin rates achieves control of the craft[7].

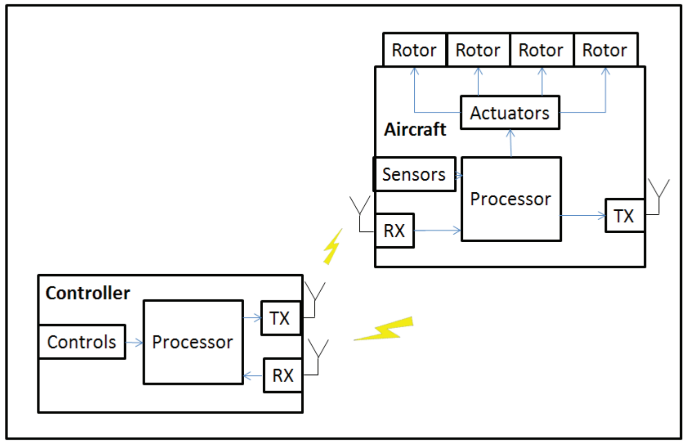


Figure 1
Block diagram of aircraft and controller.

Figure 1 is a simplified block diagram of a quadcopter aircraft and its remote controller. The processor on the controller takes its input from the joystick, other manual operator controls, and from received feedback from the aircraft. As output, the processor transmits an encoded radio signal to the aircraft. The aircraft has its own processor. The encoded radio signal from the controller is input to the aircraft's processor. The processor also receives input from sensors. Sensor information may include altitude, GPS coordinates, magnetic compass readings, wind speed and direction, battery status, and more. With this information, the processor outputs electrical signals controlling four rotor actuators that achieve flight. Simultaneously, the processor transmits an encoded radio signal back to the controller. The encoded return signal includes flight status data, which closes a feedback loop establishing stable control.

Figure 2 helps to illustrate how uplift, downfall, yaw, pitch, and roll are controlled by rotor speeds[8]. Equal thrust from all four rotors with a magnitude equal to the aircraft weight results in a stable altitude and hovering in place. Increasing the throttle increases the rotor speed, which, in turn, increases upward force or thrust, causing the aircraft to gain altitude or uplift. Decreasing the throttle decreases rotor speed and thrust, producing downfall. ("Throttle" in the context of a UAV refers to the operator control inputs and circuitry regulating the rotation rate of the electric motors.)

Yaw is a rotation about the vertical axis through an aircraft's center of gravity. Quadcopter yaw is accomplished

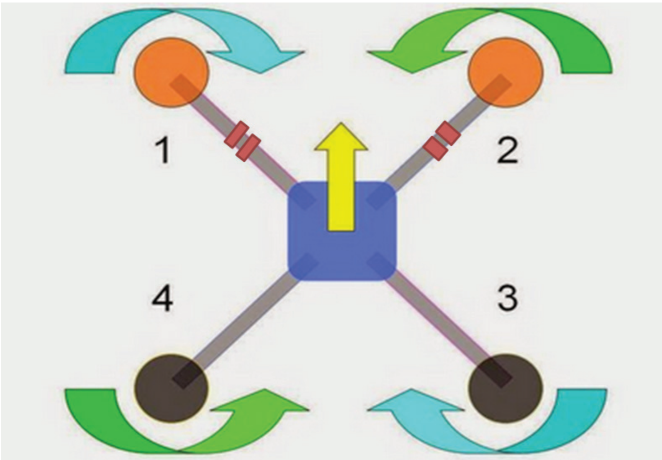


Figure 2
Rotor direction diagram for generic quadcopter[8].

by increasing the rotation speed of rotors rotating in the same direction with respect to rotors rotating in the opposite direction. In **Figure 2**, increasing the thrust of rotors 1 and 3 with respect to rotors 2 and 4 causes counterclockwise yaw; increase thrust of 2 and 4 with respect to 1 and 3 causes clockwise yaw.

On the subject quadcopter, the forward direction is indicated by contrasting color bands on two of the fuselage arms. In **Figure 2**, the red bands on the arms of rotors 1 and 2 indicate the forward direction is that of the yellow arrow. It is important for the operator to be aware of the quadcopter's orientation and forward direction. The "forward" command on the controller applies to the direction indicated by the color bands. In nearly all cases, it is recommended to orient the quadcopter so that forward is away from the operator, to avoid confusing the operator. This drone characteristic differs from radio-controlled cars and fixed-wing aircraft, which cannot be readily operated "in reverse," necessitating the use of the controls "backward" when returning to the point of origin.

Pitch means to tilt the nose of an aircraft down or up, rotating about a lateral axis. Roll means to tilt it from side to side, about a longitudinal axis. To simplify the description of pitch and roll, temporarily redefine forward as the direction of rotor 1 in **Figure 2**. If forward is the direction of rotor 1, increasing the thrust of rotor 3 with respect to the other rotors causes the quadcopter to pitch forward. Increasing the thrust of rotor 1 with respect to the other rotors causes the quadcopter to pitch backward. Increasing the thrust of rotor 4 with respect to the other rotors causes the quadcopter to roll to the right. Increasing the thrust of rotor 2 with respect to the other rotors causes the quadcopter to roll to the left.

Modern quadcopters make concern for individual rotor speeds unnecessary. The operator commands rudder and throttle through the joystick and trigger-activated buttons on a radio control (RC) unit in what is intended to be an intuitive manner, and the processor's software translates the commands into throttle control of the four rotors.

The UAS in Question

The sUAS involved in this incident comprises the aircraft with a gimbal-mounted camera mounted beneath its fuselage, the remote controller, and the application software.

Application software must be downloaded onto a separately purchased tablet or mobile phone and onto a personal computer. Two sets of hard-copy documentation are shipped with the product: a Quick Start Guide and a full User's Manual. Both the guide and manual are available online as PDF files.

Quick Start Guide

The Quick Start Guide includes:

- Disclaimers and warnings.
- A pre-flight checklist including rules of safe flying.
- Cautions regarding battery charging and usage.
- A pictorial listing of product package contents.
- Illustrated summary instructions for controls.

A point important to this case is that there is no mention of a flight data recorder anywhere in the Quick Start Guide. Assembly steps include:

- The attaching of landing gear, propellers, gimbal and camera to the aircraft.
- The charging and installing of batteries.

Flight instructions steps are:

- Power on the transmitter.
- Establish the (IEEE 802-11 b/g) radio link between controller and aircraft.
- Power on the aircraft.

- Calibrate the compass.

- Record “Home.”

- Make a short test flight.

The UAS in question makes use of GPS when six or more GPS satellites are available. The aircraft saves its GPS location as “Home” 10 seconds after it is powered up. The recorded Home may be used to automatically command the aircraft to return to its launching pad. This return routine may be configured to occur automatically as a failsafe reaction to loss of RC signal. The Quick Start Guide describes the return and failsafe routines in narrative form, graphically, and by flow chart. The return routine may not work without good GPS connectivity, and it does not attempt object avoidance. In lieu of object avoidance, the routine begins by uplifting the aircraft to a default return altitude of 65 feet above the initial operating point. This return altitude may be changed within the application software.

The Quick Start Guide describes the aircraft’s power management system, which, among other duties, monitors battery voltage. The low-voltage response of the system is described as having two levels of protection.

- The first level response displays a warning sequence of beeps and LED flashes on the remote controller.

- The second immediately forces an orderly landing with limited control still available to the operator.

The Quick Start Guide’s appendix includes:

- A table of LED Flight Indicator states and audio signal sequences to the operator.

- Aircraft specifications.

- Camera specifications.

Rules of Safe Flying

Here are key rules from the Quick Start Guide:

- Obtain some flight training before using the product for the first time.

- Check condition of all parts of the product, especially propellers and motors installation, for firmness and propeller directions.

- Make sure transmitter and aircraft batteries are fully charged.

- The transmitter to aircraft link is via IEEE 802-11 b/g. Avoid interference with other wireless equipment.

- Power sequence should always be first to power on the controller, and second to power on the aircraft. The landing sequence should be to first power off aircraft and second to power off the controller.

- Keep the aircraft 3 meters away in any direction from the operator, other people, obstacles, power lines, and sources of magnetic interference.

Online User Manual

The online user manual lists a gimbal-mounted camera with Wi-Fi video downlink, flight battery with built-in power management system, and remote-control flight controller as key features. In general, the Online User Manual has more detailed instructions, explanations, and diagrams than the Quick Start Guide.

Another point important to this case is that a so-called “beginner mode” is described in the Online User Manual but not in the Quick Start Guide. The quadcopter kit is shipped in beginner mode by default. In beginner mode, flight is restricted to within a cylinder of radius 30 meters and altitude of 30 meters (about 98 feet) from the initial operating point. In beginner mode, the aircraft is designed not to fly beyond this cylindrical boundary, but to halt and hover by means of GPS feedback when reaching any of the boundary edges. It is explicitly stated in the Online User Manual that the return routine will not work if GPS lock is lost — a fact that may be inferred from the Quick Start Guide but is not explicitly stated.

There is a flight data recorder built into the aircraft, and a battery life recorder built into the aircraft battery and power management unit. It is important to emphasize that this information, given in the Online User Manual but omitted from the Quick Start Guide, turned out to be crucial to the sequence of events of this case.

Investigation Plan

Planned External Examination and Non-Destructive Internal Examination of Crashed Aircraft and Remote Controller

Note: These steps were obviated when the drone owner dropped the case.

1. Inspect condition of aircraft and controller batteries for residual odor, deformation in shape or color change, which may have resulted from high temperature or leakage.

2. Inspect motors and brushes for evidence of shorting, which could occur from operation in rain, fog, or high humidity.

3. Inspect propeller locations and tightness.

4. Inspect landing gear installation integrity.

5. As far as possible without damaging the aircraft and controller, dismantle and inspect interior for loose wires, bad solder joints, or other visible faults.

6. Measure residual charge on aircraft and remote controller batteries.

7. Observe results of "Battery Life Test" directly on the aircraft battery package.

8. Charge the aircraft and remote controller batteries (possibly a "destructive" step). Throughout the charging process, observe the battery LED signaling sequences and compare to sequences described in the Quick Start Guide.

9. Observe the remote controller's switch settings. Check that it is set for FCC rules for North America (as opposed to European CE rules).

10. With charged batteries installed, test that aircraft and remote controller are wirelessly linked.

11. Connect the aircraft to a computer running the downloaded application software to access information from the flight data recorder and battery data recorder (possibly a "destructive" step). Expected information includes telemetry and other detailed flight data, and a battery log of charging and discharging history going back to initial factory testing. Observe all recorded events, looking for control sequences and the resulting flight pattern as well as looking for any mechanical or electronic anomalies.

12. Following instructions in the full owner manual, identify the status of the aircraft and controller calibration state, and determine if it is still valid.

13. Follow the prescribed power-up sequence for the aircraft and remote controller. Observe and record the sequence of beeps and LED patterns, comparing to expected sequences according to the manual.

14. Test that the aircraft compass module was not compromised by proximity to magnets, including (but not limited to) speaker magnets inside motor vehicles. A straightforward screening test would be to bring the system to an open area away from large metal objects, power lines, or other magnetic interferers, and compare aircraft compass readings to readings from a compass.

Planned External Examination and Non-Destructive Internal Examination of Exemplar Aircraft and Remote Controller

1. Inspect aircraft and remote controller externally and internally.

2. Charge aircraft and controller batteries.

3. Connect the aircraft to a computer running the application software to access information from the flight data recorder and battery data recorder. Expected information includes telemetry and other detailed flight data, and a battery log of charging and discharging history going back to initial factory testing. Observe all events but especially confirm expected history of either a brand new kit or the absence of any failure or derogatory log entries.

4. Perform all specified pre-flight checks.

5. Check power-on sequence of beeps and LED patterns.

6. Calibrate the known-good aircraft and controller according to instructions: Trigger calibration by exercising mode control switch, from GPS to ATTI (attitude) modes.

NOTE: In ATTI mode, control is set for equal thrust from all four rotors with a magnitude equal to the aircraft weight. With no wind, the aircraft would hover in place, but wind will change both altitude and position in ATTI mode. In GPS mode, a servo loop making use of GPS attempts to maintain a constant altitude and position.

Repeat calibration while stressing or slightly breaking rules of the calibration procedure and observe calibration response. Attempt to force a calibration failure, and follow that up with a proper calibration.

7. Perform short up/hover/down flight tests staying well within rules. On subsequent tests, attempt to push the limits of the rules.

8. Observe operation of GPS mode successfully holding the aircraft's position in wind.

9. Repeat flight test with low battery level and observe first level automatic response (LED warnings) and second level automatic response (automatic altitude drops and landing sequence).

10. Exercise the quick start manual's "Return-to-Home" fail-safe flow chart on the exemplar aircraft. Look for bad flow chart cases. Try with the subject controller as well as the exemplar controller. Try with borderline low batteries. Stress the envelope of corner cases by devising a test list that exercises combinations of parameters set to slightly beyond their specified minima and maxima. Use these as well as full online manual's instructions as of the date of the crash.

Planned Stress-Testing of Aircraft and Controller

As mentioned, the client contracted the author to determine whether a malfunction had occurred. Accordingly, the author planned to go beyond a perfunctory inspection and functional test, and to seek out deep, hard-to-find, intermittent faults. If no faults were found in the initial tests, the next step would have been to test for intermittent hardware faults on the crashed aircraft and the potential for hardware design faults or algorithmic faults on the known-good aircraft.

The stress-test plan was to conduct "constrained random tests" by crafting a computer-controlled electrical and possibly mechanical test harness to randomly "throw" switches and controls without the aircraft being in flight. Possible methods to eliminate motion during tests included:

- Modify or replace the rotor blades.
- Mechanically fasten the aircraft to a flat surface.

Constrained random sequences are a well-known approach to testing integrated circuits and software[9]. The randomness of this approach is accomplished by repeatedly and randomly exercising all switches while also varying the time interval between transitions. The constraint of the approach is to only avoid switch combinations and sequences that are specifically disallowed in the documentation. If a combination or sequence is not forbidden, then it is allowed, and should be tested — even if it not a reasonable combination or sequence.

A major characteristic of the constrained random testing approach is to apply any — and ideally all — control sequences and timings that are not specifically disallowed in the manual, even though some of the sequences or timings seem not to follow common-sense.

Note that this approach should have been followed by system design and verification engineers during the product development phase. When this process is neglected, hardware and software bugs may go undetected and find their way into finished products. A goal of product design is to be robust against non-common-sense operation of controls. The device may shut down in self defense, but should not permanently damage itself.

Possibly Destructive Tests

The second part of the planned investigation was to disassemble (possibly destructively) the kit that was involved in the incident side-by-side with a new kit shipped in its original packaging, visually inspecting and comparing each aircraft structure and mechanical/electrical content. The inspection would focus on identifying loose wires, bad solder joints, cracked circuit boards, and loose mechanical connections (among other things) that could be visibly identified as different between the two aircraft.

Planned On-Site Tests

The weather bureau archive for the date and time of the incident, taken less than eight miles from the incident, reported partly cloudy skies at 70°F with little wind. Counsel for the drone manufacturer might have argued that environmental conditions, such as electromagnetic interference, were more of a factor in the crash than any defect found by testing. In anticipation, a visit to the site was planned for the same day of the week and same time of day of the incident — to measure the presence of radio or magnetic interference and accessibility of GPS satellite signals.

Timeline of the Investigation

Immediately upon signing the expert agreement and before receiving any documentation, the author provided questions to the operator through the retaining party. They were intended only to get a feel for the incident as a starting point. Many questions were obviated by conversations with the retaining party and reading the manual and other provided documentation. The following questions illustrate the author's general troubleshooting approach:

1. How many times was the aircraft successfully flown by you or others without problems?

2. Regarding the aircraft battery:

   a. Do you always begin a flight with a fully charged aircraft battery, or is it allowable for the aircraft battery to be partially discharged at the beginning of a flight?

   b. Have you ever allowed the aircraft battery to run out during a flight?

   c. What happens when the aircraft battery runs low during a flight?

3. Regarding the battery in the controller module:

   a. Do you always begin a flight with a fully charged controller battery, or is it allowable for the controller battery to be partially discharged at the beginning of a flight?

   b. Have you ever allowed the controller battery to run out during a flight?

   c. What happens when the controller battery runs low during a flight?

4. Regarding the last flight before the flight when the incident occurred, did you notice any symptoms? For instance:

   a. Did the aircraft start to work badly or sound funny?

   b. Did the aircraft become difficult to control?

   c. After you landed it, did the aircraft smell funny, or did it feel hotter than usual?

5. On the day of the flight when the incident occurred, what was the weather like — rainy/sunny, windy, temperature?

6. At the start of the flight when the incident occurred, were the batteries full, partial or low for:

   a. Aircraft battery?

   b. Controller battery?

7. During its final flight:

   a. Did the aircraft start to malfunction, sound funny?

   b. Did it become difficult to control?

8. During its final flight: Did you fly the aircraft farther from you than usual, or did you keep it within its usual distance?

9. What happened as it fell?

   a. Propellers stopped, and it fell right down?

   b. Propellers continued to rotate but aircraft went out of control and fell?

   c. Something else?

10. After it fell, when you picked up the aircraft, did it smell funny, or did it feel hotter than usual?

The independent investigating party retained by the client, who specified that an electrical engineering expert was needed to determine whether a malfunction occurred, suggested the following procedure:

1. Read all the documents provided.

2. Obtain answers to any remaining questions.

3. Draw up a time and expenses estimate based upon the intended investigation procedure.

4. Do not purchase anything until authorized.

The aircraft operator's attorney provided these statements from the aircraft operator to the retaining party:

- It was the first time the operator had flown the aircraft.

- The operator told her attorney that the aircraft went out of control and hit a bystander in the head.

- The operator and the injured bystander walked to a nearby police outpost and filed a report.

- No medical care was given, requested, or offered.

- The operator's attorney told the retaining party that the operator was a busy professional and had no time to speak with the retaining party or answer further questions.

- The operator said that she had reviewed the Quick Start Guide in detail but only briefed the user's manual.

The client's planned interaction with the operator and her attorney incorporated the following actions:

- Contact the operator and set up a meeting at her home.

- Measure and photograph all aspects of the drone and the box it was in.

- Obtain the size and weight of the aircraft.

- Photograph any instruction manuals.

- Photograph the operator's original receipt for date of purchase.

- Identify warning labels.

- Request the name and contact information of the operator's friend that was present at the time of the incident as a possible witness.

- Take a recorded statement from the operator and the operator's friend of what happened.

- Determine the approximate location of the operator and operator's friend, as well as the location of the struck party.

- Travel to the playground and photograph of the incident location.

- Photograph the operator holding the drone, and their height and weight for handling purposes of the drone.

Documentation provided by the client included:

- Photographs:

    o Ground-level photos of the scene.

    o Satellite aerial views of the incident location, some marked by the operator.

    o Dimensional and weight measurement photos of the kit contents from multiple angles.

    o Packaging photos.

    o Warning message photos.

- E-mail messages between the operator's attorney and the retaining client showing the provided questions and answers by the operator.

- The police report.

- The retaining client's report.

- The two manuals.

Conclusions

The following considerations were made and actions taken after reading the documents. In the first and only flight by the operator, she violated safety and operating rules and suggestions within the manuals. The operator did not obtain flight training from a professional or practice flying on an online flight simulator, as advised in the full manual and the quick start. The operator removed the camera from the aircraft for the flight in question, which violated the specific instructions of the full manual (but not the quick start guide) that the camera should always be mounted on the aircraft, and that the mounted camera is necessary for stable flight.

The public park in the center of a city where the incident-related flight took place was unsuitable for flying, and the operator should not have attempted to fly the aircraft at that location. The presence of people, trees, and powerlines rendered the site unsuitable for safe flying, according to both the quick start and full manuals. Both manuals say not to operate near other people, near power lines that may cause magnetic interference, or near tall buildings which may compromise GPS operation.

Even considering the unsuitability of the flight location, the potential of a malfunction remained. Any malfunction discovered would have to be significant enough to outweigh the contributions by the actions of the operator. The operator's response that she only "briefed" the user's manual also implies she may not have been aware of the flight data recorders.

The author contacted the retaining client, requesting to ask the owner/operator if she was aware of the existence of flight and battery data recorders, stating that one of the first planned investigative actions was to review the flight data. The full planned investigation and testing would be expensive, and — even if hardware or software faults were found — the opposing side may point out all the violations of rules and guidelines as major contributing factors to the incident. Therefore, no further inspection or testing would be completed until approved by the owner/operator. Within two days, the client responded that the drone operator decided to drop the investigation and settle the matter immediately.

As Fred H. Taylor aptly put it[10],

"This study demonstrates how the [forensic engineer] may protect the client from making a serious or costly mistake through unsubstantiated litigation. One of the services the [forensic engineer] must provide is to evaluate and challenge a situation as early as possible so the client knows how valid his or her position is before pursuing a claim or litigation."

References

1. D. Lenz, "Navigating Quickly Crowding Skies," *PE Magazine*, p. 8, Dec. 2016.

2. T. Foster, "10 Ways Drones Are Changing Your World," *Consumer Reports*, pp. 45-51, Jan. 2017.

3. W. Kalif, "Timeline of Radio Control," Storm the Castle.com, 2016. [Online]: Available: http://www.stormthecastle.com/model-airplanes/timeline-of-radio-control.htm. [Accessed 15 May 2018].

4. P. C. Miller, "Consumer drone sales expected to skyrocket in coming decade," UAS Magazine, 21 January 2016. [Online]: Available: http://www.uasmagazine.com/articles/1403/consumer%E2%80%90drone%E2%80%90sales%E2%80%90expected%E2%80%90to%E2%80%90skyrocket%E2%80%90in%E2%80%90coming%E2%80%90decade. [Accessed 15 May 2018].

5. Federal Aviation Administration, Washington DC, "Subtitle B—Unmanned Aircraft Systems," 29 August 2017. [Online]: Available: https://www.faa.gov/uas/media/Sec_331_336_UAS.pdf. [Accessed 15 May 2018].

6. Federal Aviation Administration, Washington, DC, "FAA sUAS PART 107: THE SMALL UAS RULE," 29 August 2017. [Online]: Available: https://www.faa.gov/uas/media/faa-uas-part107-flyer.pdf. [Accessed 15 May 2018].

7. Quadcopter Arena, "The History of Drones and Quadcopters," QuadcopterArena.com, 2018. [Online]: Available: https://quadcopterarena.com/the-history-of-drones-and-quadcopters/. [Accessed 15 May 2018].

8. "Fly your Way! An Ultimate resource for Quadcopters and Drones," Quadcopterflyers.com, 2017. [Online]: Available: http://www.quadcopterflyers.com/2015/02/quadcopters-yaw-roll-and-pitch-defined.html. [Accessed 15 May 2018].

9. D. Shleifman and V. Besyakov, "Constrained Random Test Environment for SoC Verification using VERA," in *SNUG*, Boston, 2002.

10. F. H. Taylor, "Environmental Systems Failures," in *Forensic Engineering*, New York, Elsevier Science Publishing Co., Inc, 1989, p. 256.

Forensic Engineering Analysis of a Fatal Trailer Wheel-Separation Failure

By Stephen A. Batzer, PhD, PE (NAFE 677M)

Abstract

A forensic analysis of a fatal trailer wheel-separation failure is presented in this paper. An older three-axle trailer carrying snowmobiles was being driven at highway speed during winter time in Michigan. The left front wheel detached due to the catastrophic failure of all six lug studs. The wheel traveled into the on-coming traffic lane and struck the roof of a sedan driven by a local student. The driver of this vehicle was killed instantly due to passenger compartment intrusion. One possibility was that the lug nuts were improperly tightened during a recently performed service — and that this looseness diminished clamping forces and led to cantilever bending of the studs and fatigue fracture. An analysis of the defendant's narrative and of the failure were performed.

Keywords

Trailer, torque, lug nut, wheel detachment, clamp force, fatigue, corrosion, forensic engineering

Accident Overview

According to the state crash report, "Vehicle one was traveling N/B when the front driver's side tire came off of the trailer, crossed the median barrier, and struck vehicle two going S/B. Ultimately, the driver in vehicle two was killed as a result of this accident." The conditions were cloudy, daylight, and cold, with a dry roadway and no snow. The towing vehicle was a Ford Expedition with three occupants. They were traveling out of state for a snowmobile trip. The accident trailer with the failed wheel had three axles with a Gross Vehicle Weight Rating (GVWR) of 15,600 pounds. The southbound driver of the oncoming sedan was killed instantly as the wheel and tire struck the windshield header (the roof header buckled, and struck the driver in the head). The police diagram illustrating the accident is shown in **Figure 1**. The trailer is shown directly after the accident in **Figure 2**.

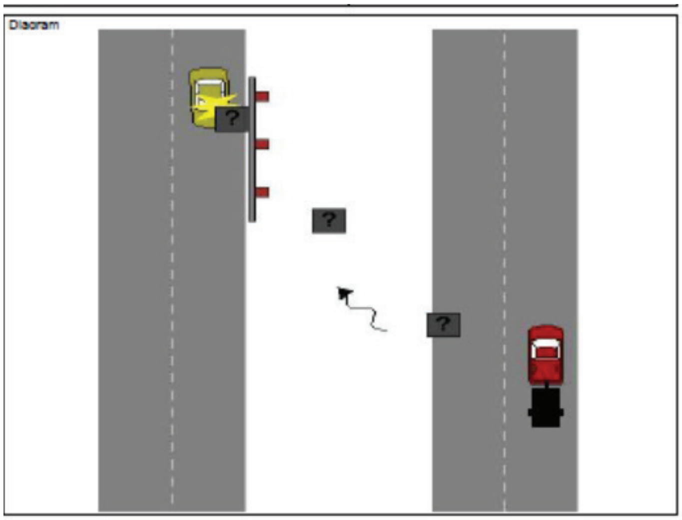


Figure 1
Accident diagram from police report.

Figure 2
Accident trailer at a gasoline station; the left front wheel is missing.

Stephen A. Batzer, PhD, PE, 8383 State Road M113E, Fife Lake, MI 49633, 479-466-7435; batzer@batzerengineering.com.

When interviewed, the Expedition driver indicated to the police that he exited the highway and stopped at a gas station when he realized something might be wrong with the trailer. He determined that he had lost a wheel, and remembered witnessing ambulances going southbound. He called 911 in the event that the ambulances had anything to do with the wheel detachment. He was called back by state police who told him that the wheel had killed the oncoming driver — and to stay put until they could investigate. The Expedition driver was interviewed along with the other two vehicle occupants. There was no suspicion of alcohol usage, and no citations were issued.

The driver of the Expedition did not own the trailer, which was used for interstate commerce. It was owned by his employer. The trailer was built in 2000, making it 13 years old at the time of the wheel detachment. There were no written maintenance records for the trailer. Within a month prior to the incident, the trailer had been serviced and repaired. The mechanic of the company that owned the trailer did the work. After elevating the trailer, each wheel was removed, and the bearings were greased. Three tires were replaced, including the left front along with its wheel. The brakes were checked for proper function. The mechanic testified that standard practice was to put the wheel/tire combination on, put on the lug nuts, and snug them up to lightly seated, using a quarter-inch, battery-operated drive electric wrench. Then he lowered the trailer to the ground and used a torque wrench to seat them, with a specification of 100 foot-pounds for half-inch studs, which he derived from an information sheet from a tire retailer. He testified that he torqued all the trailer's lug nuts using a torque wrench that had been recently calibrated.

On the night of the accident, the trailer mechanic was informed of what happened. He drove 150 miles to the gas station, bringing his torque wrench and checking all remaining nuts. He testified that they were not loose and had been properly torqued. The trailer was driven back without unloading the contents. Although only two wheels remained on the left side, there were no further incidents.

Forensic Analysis

An obvious candidate cause of the detachment was loose lug nuts — that is, after the left front new wheel and tire were mounted, the lug nuts were snugged into position but not properly torqued. The evidence was compared to this hypothesis and others. Not all evidence could be analyzed, as the stud ends and lug nuts were lost. However, neither of these losses consequentially diminished the confidence of the analysis. The six lug studs were not newly installed, and they had not failed previously under similar use — which represents a field test of their performance. The remnants of the studs were carefully examined using a variety of sophisticated techniques. Lastly, the six lug nuts that were not recovered had not been replaced just prior to the failure, and had not failed in previous service, which represented another field performance test.

The wheel, tire, hub, and stud remnants were examined, according to a mutually agreed-to joint protocol at a regional metallurgical lab. Both plaintiff and defense experts were present at the time of the inspection. The materials present for the examination included:

1. Detached damaged wheel.
2. Tire (still mounted to the wheel).
3. Hub (containing six lug stud remnants).
4. Subject torque wrench and calibration certificate.

The damage to the stamped steel wheel (**Figure 3**), shows that there had been significant undesirable rotational interaction between the wheel and the studs prior to stud failure. The observed damage to the stud holes must have occurred during the trip. It is not credible that anyone would mount a wheel that showed damage of the sort evident on the wheel. The elongation of the mounting holes showed violent and sustained back-and-forth relative motion of the wheel relative to the hub. Marking on the wheel indicated that it had a 2,600-pound capacity, which indicated that the six-wheel trailer could hold a nominal 15,600 pounds on the wheels plus some additional load through the tongue and trailer hitch. Since the trailer's GVWR was 15,600 pounds (as listed on the data plate), the detached wheel was of the appropriate weight capacity. Loading was also not an issue for the tire, nor the contents, as the driver of the Expedition estimated that the total trailer load was only 6,500 pounds. Furthermore, there was no problem encountered when the trailer was driven back with the same load on only five wheels.

The wheel was in new condition when mounted prior to the subject trip. As shown in **Figure 3**, the detached wheel showed no rust whatsoever, while the other wheels on the trailer exhibited light to moderate rust.

Figure 4 demonstrates both sides of the trailer in storage. These photos were taken after the trailer had been

Figure 3
Wheel at point of rest at the accident scene. Note rust-free exterior.

repaired, as six wheels (not five) were present. In addition, the wheels do not correspond one-to-one to scene photographs. They are in varying states of corrosion, and the wheel cutouts do not match, indicating that the wheels are not identical in model. This shows that various wheels had likely been replaced over time on this trailer.

Figure 5 shows the trailer's left side front hub at the scene. Flaking rust plausibly diminishes the ability of the studs to provide the clamping force that fixes the wheel to the hub. This friction is necessary to prevent the wheel from slipping and rotating relative to the hub and damaging the lug studs. There are several high points that wore through the flaking rust near the periphery of each mounting interface. Three of these are called out with red arrows. This photo also documents that the grease cap was dislodged during the wheel loss. Five of the six fractured studs are visible in this photograph. Each shows a silver-colored fresh fracture surface. The two studs at 12 o'clock and 2 o'clock are broken below flush. The fracture surfaces of these two studs are in the vicinity of the stud splines. This indicates that the mounting studs were subject to damaging cantilever bending moments, and their mounting holes through the hub were distorted. Note: In this picture, the 6 o'clock stud is not visible, and the 8 o'clock stud has

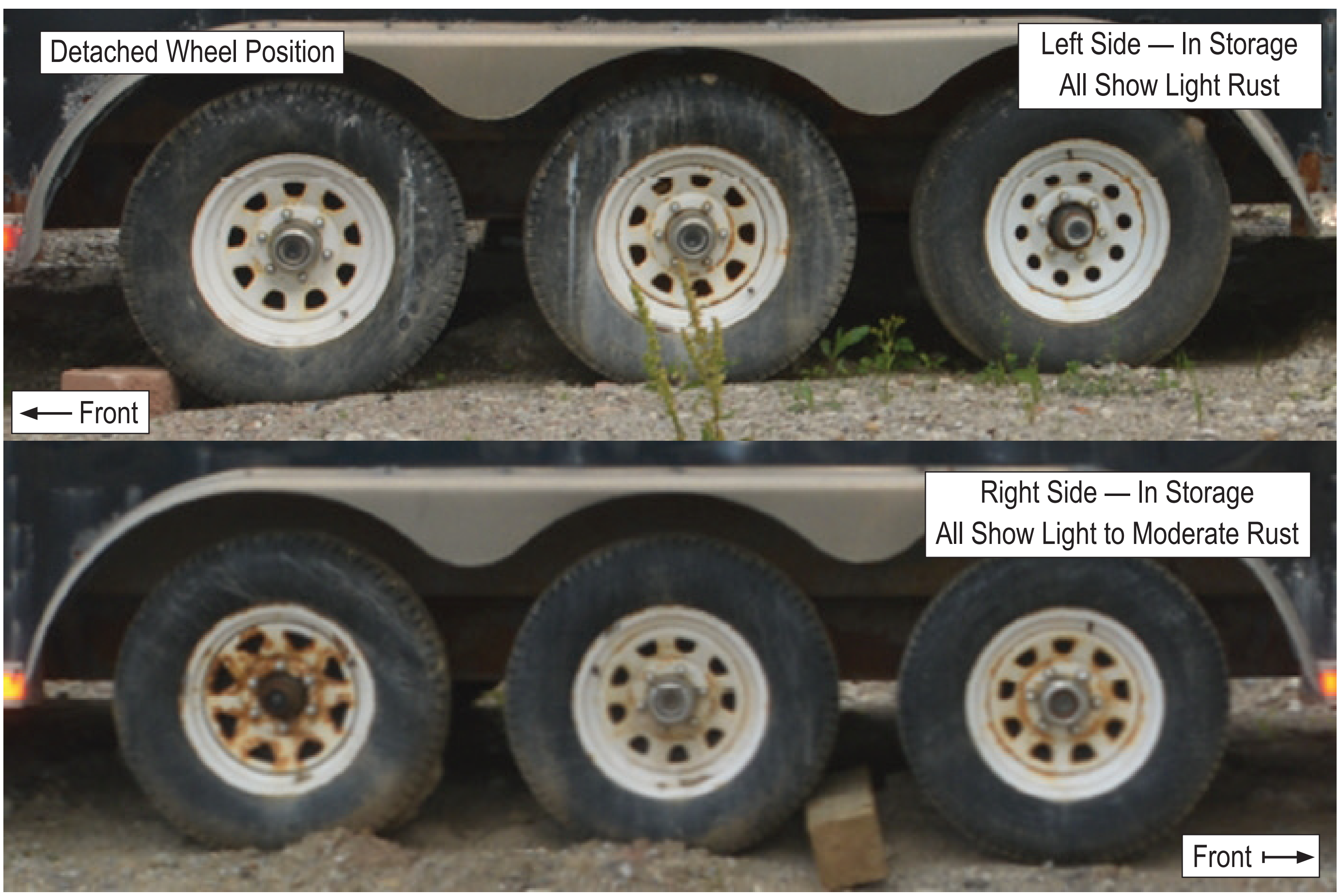


Figure 4
Accident trailer at a gasoline station; the left front wheel is missing.

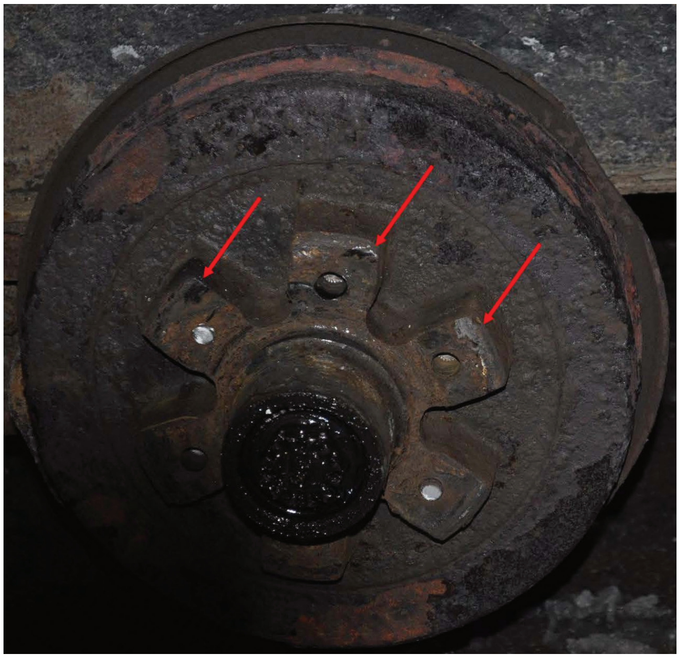


Figure 5
Accident trailer left front hub at time of accident.

fractured below flush and is only barely visible. While this hub is rusty, it is not any rustier than the five other hubs, which did not fail. Therefore, the rust is not a reasonable explanation to the loss of clamping force and failure.

Examination of the hub, studs, and wheel from scene photographs showed consistent evidence of fatigue failure mechanism of the studs. In this mode, the six studs were damaged simultaneously, but they failed sequentially. **Figure 6** shows a close-up photograph of the failed wheel (at left) and the hub (at right). The least-damaged mounting hole was labeled 1. The remaining holes were labeled 2 through 6 clockwise. Shown to the right of the wheel photograph is a close-up photograph of the hub, in what is believed to be the same orientation as it was during the incident to match the wheel (hub stud position A was assembled to wheel hole 1). Note that during the forensic investigation, the studs were not labeled as they are for this paper, as the comparison and analysis had not been made. That is, the original choice of which stud was “A” was made at random, and the stud originally labeled “A” did not line up with wheel hole position 1.

The basis for the postulated match-up of wheel to hub was comparison of maximum damage at each position. Therefore, it is reasonable to assert that the maximum wheel damage, as evidenced by the most elongation of the stud mounting holes, matches the maximum hub damage, as shown by below-flush fracture of the studs. The three most damaged holes are B, C, and F. These correlate to the same positions on the aligned hub photo 2, 3, and 6. Note that the wheel in **Figure 6** is shown from the outboard side, so the hole to stud positions match; they are not mirror images, which they would be if the mounting face of the wheel were shown.

During the initial wheel wobble (due to loose lug nuts), each stud was identically loaded, more or less, by

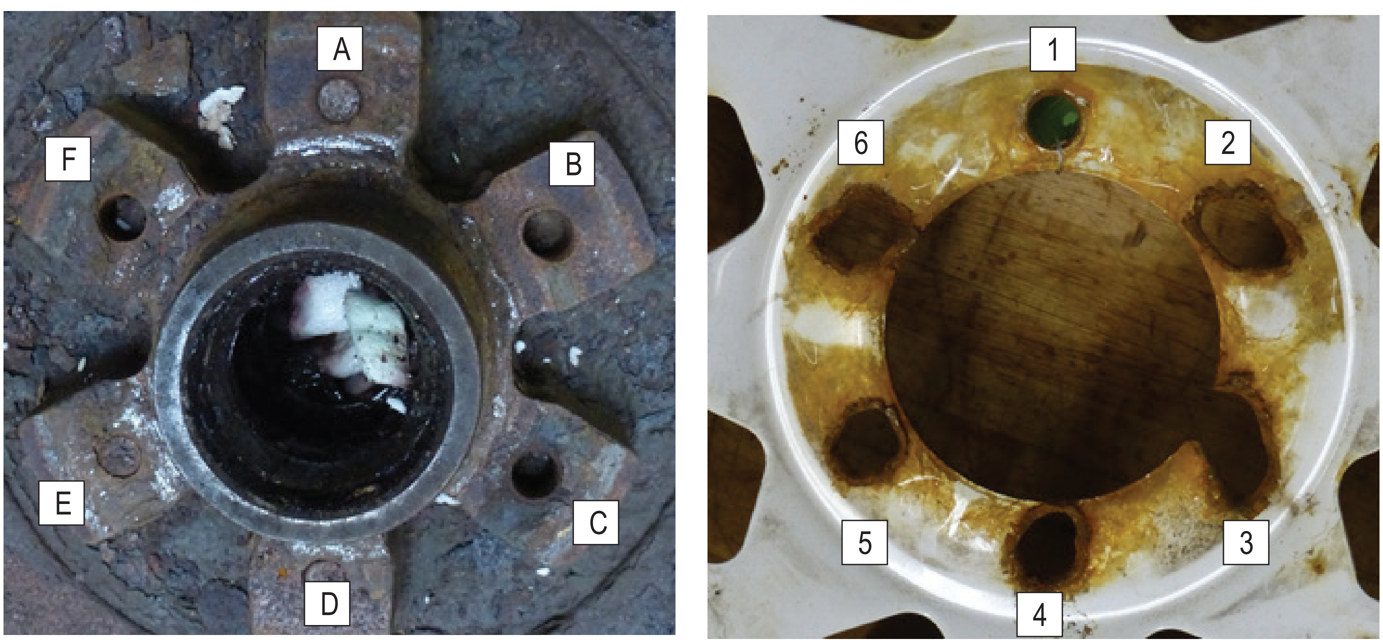
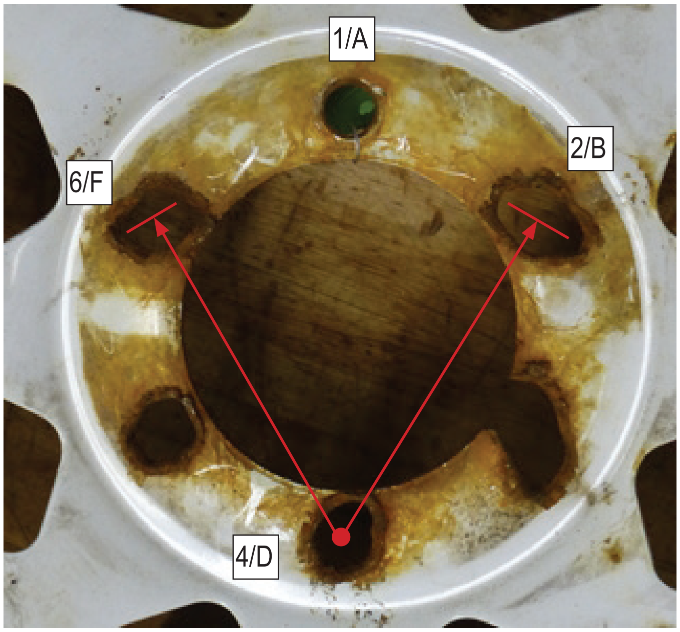


Figure 6
Accident trailer wheel and hub oriented to most likely mounting alignment.



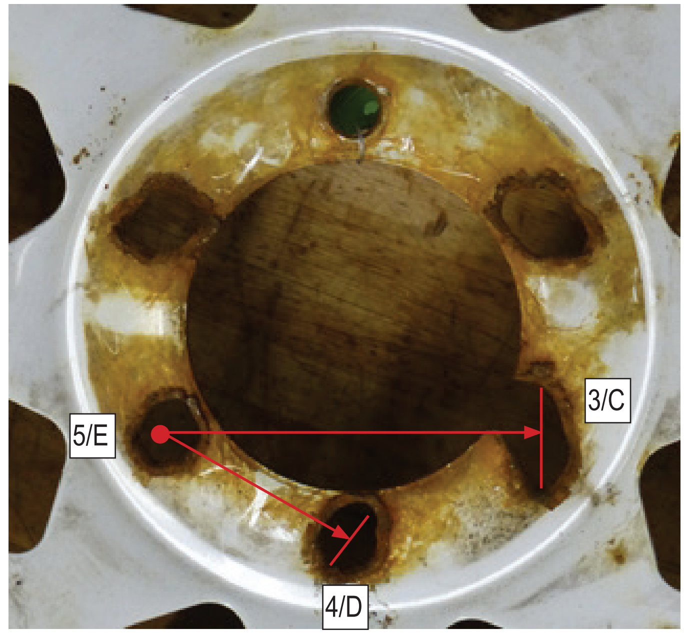


Figure 7
Graphic analysis of stud fracture sequence caused by changing fixation forces.

the impacting steel wheel, and the studs impacted the holes in an orbital motion, causing circumferential damage. At some point, a single stud fractured during this most minimal early stage of damage. This was hub stud A and wheel hole 1, as shown in **Figure 6**. After stud A at wheel hole position 1 fractured, each wheel hole was more or less round due to previous uniform circumferential impacts by the studs. With only five studs remaining, the wheel was less rotationally constrained, and the holes/studs adjacent to hole 1 (that is, hole 2 / stud B and hole 6 / stud F) were disproportionately and incrementally damaged as the wheel rotated approximately about stud D, which is opposite fractured stud A. This caused studs B and F to fracture in close succession, although which of the two studs fractured first is not clear. After studs A, B, and F fractured, the holes at those positions (1, 2, and 6) were no longer damaged. With three remaining studs (C, D, and E), the wheel was even less constrained, and damage occurred to these remaining three studs at an accelerated rate. The damage at wheel hole 3 shows that the wheel rotated about stud E. Both wheel holes 3 and 4 show this damage of rotation about hole 5 / stud E, and studs C and D failed in quick succession. Wheel hole position 4 shows less damage than does wheel hole position 3. Thus, stud D likely fractured before stud C. Stud E failed last, freeing the wheel and tire, which departed and struck the oncoming vehicle. Thus, the progression (as based upon the damage analysis) was likely stud A, next studs B and F, then stud D and C, and finally stud E. This analysis is shown graphically in **Figure 7**.

Tire Analysis

Examination of the accident tire shows that it was in new condition at the time of mounting, just prior to the wheel detachment (**Figure 8**). The measured tire tread depth measured minimum 9/32 inches while new tread depth is 10/32 inches. This is a radial tubeless tire, size ST225/75R15, labeled “FOR TRAILER SERVICE.” Maximum load is 2,830 pounds, Load Range E, 80 psi maximum. The overall diameter is 28.5 inches. As the photo documents, the mold sprues were still present.

Stud Metallurgical Analysis

To determine if the studs incorporated a material defect, they needed to be removed from the hub and destructively tested. Prior to destructively cutting into the hub to remove each stud, outside fracture and inside head surfaces were examined using an optical microscope. Each stud was an SAE (Society of Automotive Engineers) ½-20 Grade 8 fastener (**Figure 9**). This means the thread body is nominally ½ inch in diameter with 20 threads per inch. Grade 8 fasteners are medium-carbon alloy steel that has been heat treated. This means that they have been heated above their austenitization temperature and then quenched/tempered. These studs were pressed into an interference fit within the hub using splines. The mating hole had been counter-bored to accept the head. The heads are round without wrench flats. The SAE grade marking is evidenced by six radial marks, shown at the lower left photo. The manufacturer’s mark W appeared at the periphery of each head, as shown at lower right. By

Figure 8
Accident trailer tire showing manufacturing sprues and deep tread.

referencing the Fastener Quality Act registry[1], it was determined that these studs were manufactured by Westland Steel Products, Winnipeg, Canada.

Since this trailer was used in the Midwest, it was operated in the presence of road salt and moisture, which acted as corroding agents. Each stud fracture surface segment was given a stabilized hydrochloric acid cleaning

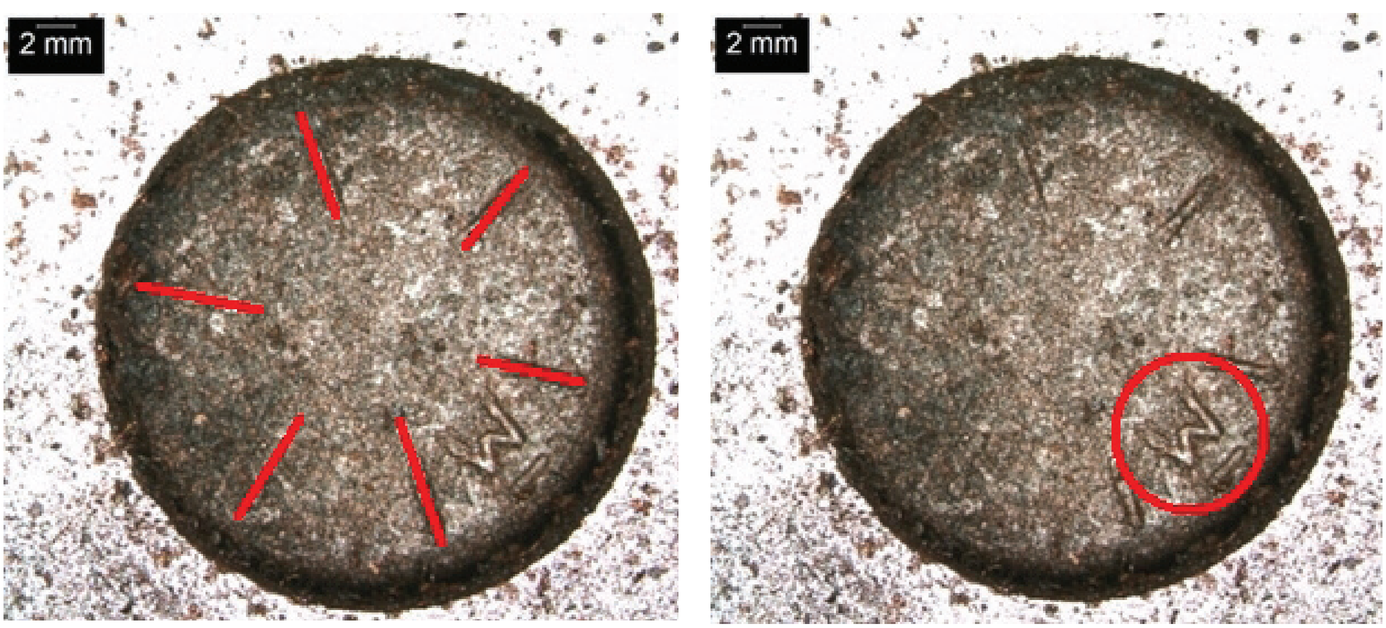


Figure 9
Stud marking indicating SAE grade (left, highlighted in red) and manufacturer (head stamp encircled in red highlight).

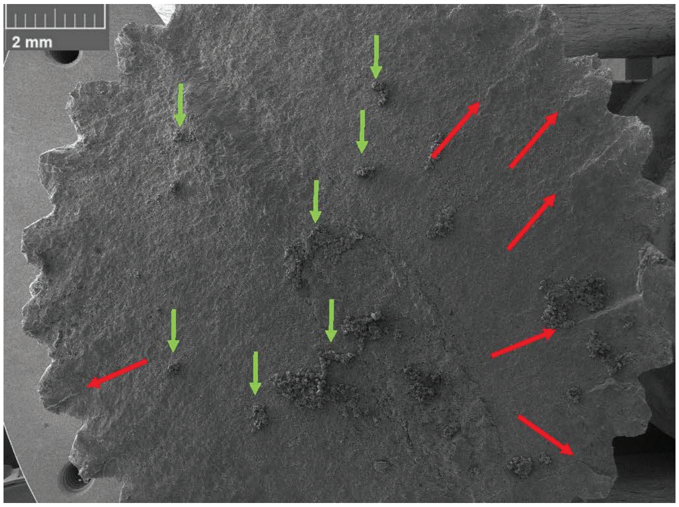


Figure 10
SEM photograph of stud fracture surface.

bath to remove superficial corrosion. Each stud was removed from the bath before the corrosion transformation was complete to prevent collateral damage. The remaining corrosion is clearly depicted by the SEM (scanning electron microscope) photograph set forth in **Figure 10**. Various untransformed surface corrosion areas on the fracture surface of stud A are called out with short downward-facing green arrows.

Element	Wt %	Method	Comment
Fe	Matrix	ISO1	Base metal
Mn	0.79	ISO1	Alloying element
C	0.39	L	Strengthening element
Si	0.21	ISO1	Alloying element
Mo	0.21	ISO1	Alloying element
Cu	0.07	ISO1	Recycling impurity
Cr	0.03	ISO1	Recycling impurity
Ni	0.03	ISO1	Recycling impurity
S	0.016	L	Ore impurity
P	0.007	ISO1	Ore impurity
Co	0.006	ISO1	Recycling impurity
W	<0.01	ISO1	Below Detection Limit
V	<0.005	ISO1	Below Detection Limit
Al	<0.005	ISO1	Below Detection Limit
Ti	<0.005	ISO1	Below Detection Limit
Zr	<0.005	ISO1	Below Detection Limit
Nb	<0.005	ISO1	Below Detection Limit
Ta	<0.005	ISO1	Below Detection Limit
B	<0.0005	ISO1	Below Detection Limit

Figure 11
EDS analysis of representative stud.

A macro-indication of fatigue is contained in the SEM photograph. These ratchet marks are called out by red arrows pointing to the periphery, which, in this case, are the splines. SEM photographs of studs A, B, C, E, and F exhibited peripheral ratchet marks, a common feature of fatigue initiation. The uncleaned fracture surface of stud F was subjected to an EDS (energy dispersive spectroscopy) analysis. The principal elements recorded included Fe, O, C, Ca, Cl, Si, and Mn, as documented in **Figure 11**. Trace aluminum was also present. The explanation of each element is straightforward. Iron (Fe) and manganese (Mn) are components of the steel. Oxygen is ubiquitously present and a component of the corrosion product. Carbon may come from oil or biological contamination. Calcium (Ca) and chlorine (Cl) are present in road salt, and are contained in the corrosion products. The aluminum likely came from bearing grease or dirt. A portion of stud F was then destructively tested to provide bulk composition analysis to determine conformance with grade 8 fastener composition. The results of this further analysis are recorded in tabular form in **Figure 11**.

The EDS analysis is consistent with 4037 steel, which is an appropriate alloy for heat treated Grade 8 threaded fasteners. Metallography was conducted on a longitudinal segment of a representative stud (**Figure 12**). This sampling technique was appropriate as the raw material used to manufacture these studs is drawn wire, which produces linear inclusions. No objectionable impurities or pores were detected.

The stud sample was then given a nital (nitric acid 2% in alcohol) etch. This revealed the microstructure as shown in **Figure 13**. This photograph shows martensite,

Figure 12
Metallographic sample of representative stud to examine inclusions.

Figure 13
Metallographic sample of representative stud to examine grain structure.

indicative of an austenitized, quenched and tempered heat treatment to provide strength and toughness. No objectionable grain structure or alloy segregation was detected.

It was agreed by the experts to do no tensile tests unless something "unexpected" occurred during analysis. In a practical sense, that agreement between the experts meant that no tensile tests would be conducted if no outlier hardness test results were produced. Core hardness tests were taken. The results are tabulated in **Figure 14**.

The minimum measured average hardness was 34.4 HRC, and the maximum average hardness was 35.5 HRC, a difference of 1.1 points. The hardness testing measurement of a sample is used to accurately estimate the tensile strength. The approximate tensile strength of a sample with a uniform HRC 34 hardness is approximately 155,000 pounds per square inch (psi)[2]. For 35 HRC, the approximate tensile strength is 160,000 psi. For a uniform hardness of 36 HRC, the tensile strength is approximately 165,000 psi. For the minimum measured fastener with a hardness of 34 HRC, the tensile strength (by interpolation) should be 157,000 psi. Studs with a ½-20 thread have a stress area of 0.1599 square inches (in^2). This gives a calculated minimum tensile strength of 25,104 pounds. These studs have a tensile strength minimum requirement of 24,000 pounds, and thus the hardness measurements

Stud	Measured Average Hardness (HRC)	Stud	Measured Average Hardness (HRC)
A	34.9	D	35.5
B	35.5	E	34.6
C	34.4	F	35.0

Figure 14
Hardness test of each recovered stud remnant.

evidence that the tensile strength of each stud was within the SAE specification. Note that fatigue resistance is well correlated with hardness. When used in a properly designed wheel fastening system, these studs should be "fatigue proof" for this application in the absence of severe corrosion, usage, or mounting error.

When examined, the cleaned fracture surfaces of the studs showed a variety of features, including residual corrosion products, rubbing of the fracture surfaces, overload dimpling, and fatigue marks. Three different stud SEM micrographs are now shown. The most frequent observation was "no fracture data," as is shown in **Figure 15**. **Figure 16** shows a region of a stud with residual corrosion products and overload dimples. **Figure 17** shows what was found clearly in five of the six studs: fatigue crack marks. As for the sixth stud, which did not show clear

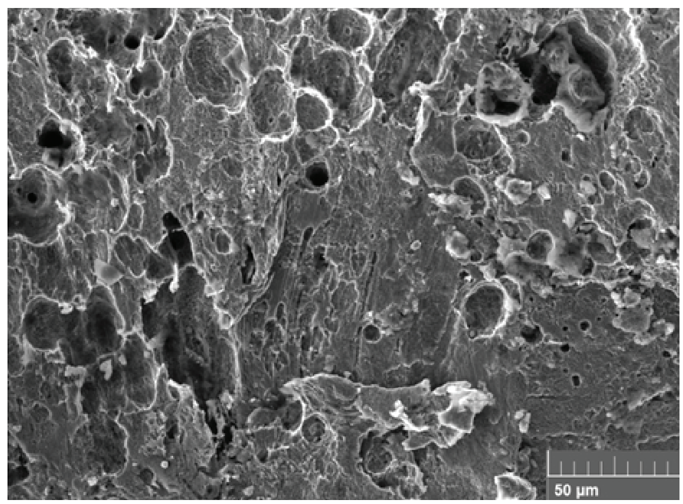


Figure 15
Corrosion pits caused by acid during cleaning.

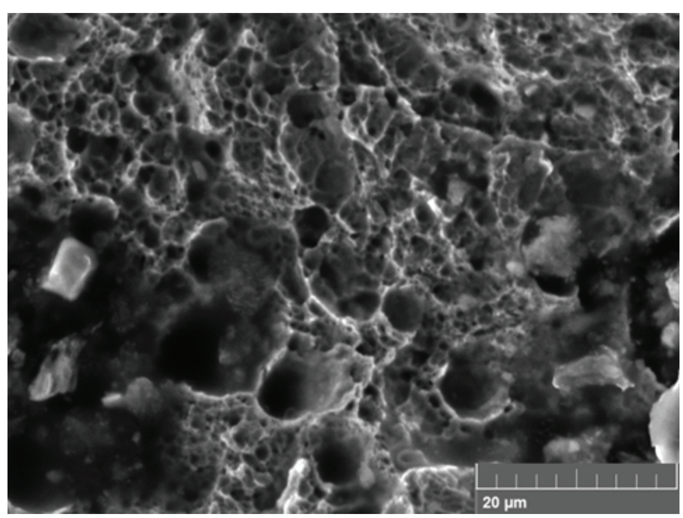


Figure 16
Overload fracture with some residual corrosion products.

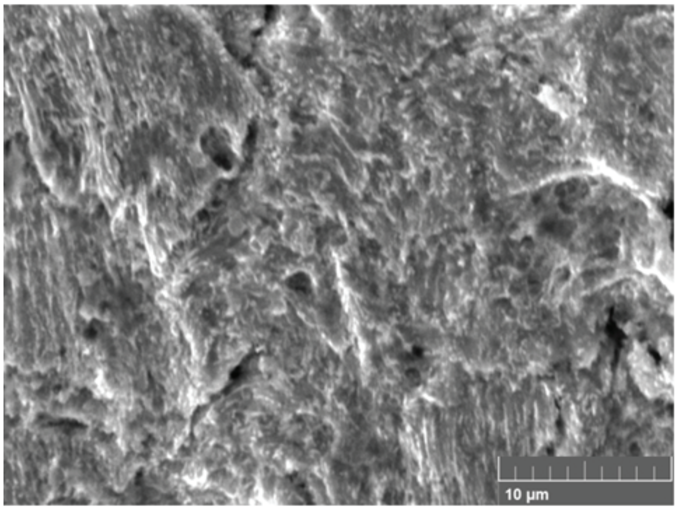


Figure 17
Fatigue striations documenting the stud failure mechanism.

residual fatigue marks, fatigue as a failure mechanism could not be eliminated.

Trailer Destructive Testing

To better understand the progression of the damage to failure, destructive testing was conducted using an exemplar trailer. A 16-foot-long unenclosed conventional ball hitch flat trailer with two axles was purchased new for the testing. This was demonstrative testing to shed light on trailer wheel detachment. It was not performed to replicate the accident. The test setup is shown in **Figure 18**.

The four white steel wheels were each mounted to six studs identical in specification to those of the subject trailer. The wheels had tires (ST225/75R15) labeled for trailer service only. The tires were inflated to their normal pressure of 65 psi cold. The wheel chosen to fail was the right side rear wheel. This choice of tested wheel position was done for safety. The right-side wheel does not face oncoming traffic, and the front wheel is somewhat closer to the center of gravity of the trailer as loaded — and should better support the loading once the tested wheel failed. The trailer load was a 1999 Ford Explorer 4-door SUV; the weight was approximately 3,700 pounds. The goal was to drive at somewhat less than highway speed on rural "farm to market" roadways until a stud failed, but before the tested wheel detached. Each lug nut was put on hand tight. Holes were cross drilled through the studs to accommodate cotter pins, which prevented complete loss of the nuts.

The trailer was run with two wheels on the right-hand side for approximately 104 miles of travel with a combination of closed track travel and travel on rural Michigan roads. Frequent stops, on the order of every five miles, were made to check on the condition of the wheel. The test was done by a driver and a passenger, whose job was to watch the wheel for out-of-plane wobble during travel using an extended side mirror. The wheel stud threads were progressively damaged, but it was not obvious that the studs would fail in a reasonable amount of time with the loading conditions chosen. Thus, the right front trailer wheel was removed to double the force against the right rear wheel and accelerate the damage to the studs. After this doubling of load, continued testing was limited to a closed asphalt track. It was noted that two lug nuts would automatically cinch up against the wheel and provide a more secure wheel against the hub — a known performance characteristic of right-handed fastener threads on right handed wheels. One of these lug nuts was removed, and the testing was continued on the track with only five lug nuts — four of which were loose and one of which was tight. The nut that was removed was marked with red ink, as was its mounting stud. After 11 miles on the asphalt closed track, a single stud had broken, and the testing was suspended.

The wheel at the time of the suspension of the testing is shown in **Figure 19**. Notice that the one hole with the removed nut is marked in red and is at the 12:00 position.

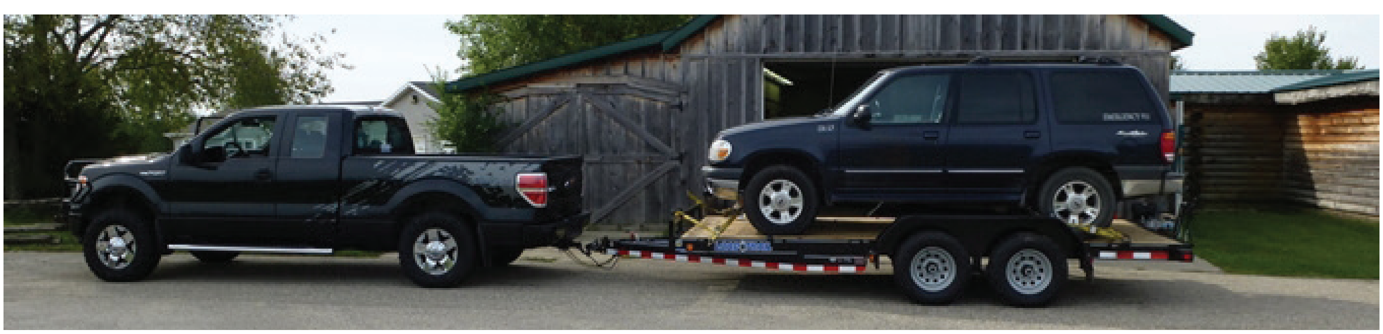


Figure 18
Setup of trailer wheel testing.

Figure 19
Trailer wheel directly after first stud fracture showing the position of the fractured stud.

At the 2:00 position is the failed stud. This stud failed below the surface of the hub, as was seen in 50% of the accident trailer stud failures.

At no time during the testing did any wobble of the wheel give a tactile feedback to the driver or the passenger tasked with observing the wheel. This testing provided valuable experience regarding the progression of the failure of the studs of the accident trailer. In the both cases, as the loosely held wheel moved relative to the studs, the holes enlarged due to striking the studs in a rapid and circumferential fashion. This accounted for the enlarging of the holes seen on the incident and test wheels. It also accounted for the substantial thread damage that was seen on the test studs, but that could not be documented on the failed trailer studs — as those studs were not recovered. Wheel paint damage at the inboard side of the wheel was observed on both the failed accident trailer and the test wheel. Another detail the test confirmed was that in this sort of loading the studs fail progressively, not all at once. Another similarity of the test to the accident is that the first stud to fail left a largely circular enlarged mounting hole in the wheel.

Forensic Methodology Documentation

The forensic methodology used in this investigation is outlined in the text, "How to Organize and Run a Failure Investigation" by Dennies[3]. The task outline, as given by Dr. Dennies, is reprinted below along with tasks that were followed. The text reprinted below was included within the expert report and was provided in anticipation of a Daubert challenge. This text is modestly changed to remove the names of the involved parties.

1. Understand and negotiate the investigation goals.

The client and investigator discussed qualifications and methodology at length with the client prior to the investigation. It was noted that this was a typical assignment. Nothing was found to be particularly unusual about the circumstances of this unwanted wheel detachment.

2. Obtain a clear understanding of the failure.

All information made available was reviewed, and both visual analysis/destructive testing of the relevant artifact was conducted. The failure consisted of the unwanted fracture of the six lug studs at the left forward wheel of the towed trailer. None of the other components (tire, wheel, hub, lug nuts, or bearing) failed, though several of these components were damaged. The evidence indicates that an initial fatigue crack at each stud formed and then progressed until final separation of the outer aspect of the stud from the root. According to the classic text "Understanding How Components Fail" by Donald Wulpi, there are numerous other damage classifications for a failure besides fatigue. These modes are discussed below:

- Distortion. This was not a distortion failure, although the hub did distort during the chain of events that led to failure. The wheel was lost by fracture of the studs. The studs did not fail because they changed shape, as a wooden door can fail when it warps over time. The hub and wheel did not show distortion; they both showed damage from impact as the loose wheel repeatedly struck the studs.

- Basic Single Load Fracture. This failure mode indicates that a single event caused the failure, such as a baseball striking a window. This mode did not occur. Had there been a single overload, there would be other indicators present, such as a damaged tire or wheel rim, and other wheels on the left-hand side would have likely shown similar damage.

- Wear. The components did not wear out; they were rapidly damaged progressively throughout the trip. The wheel showed no abrasive wear. The tire was practically new, although the trip obviously caused accelerated tread wear as the tire wobbled. No significant wear — only corrosion — was observed for the hub and studs.

- Corrosion. The new tire and new wheel were uncorroded. The hub and studs both showed surface corrosion. However, the accident hub and studs were not significantly different than at the five other positions of the trailer. Thus, corrosion as a causative mechanism of stud failure and wheel detachment can be safely rejected.

- Temperature Related Failure. The conditions were neither severely hot nor cold. Had the operating temperature been objectionable, other wheel positions would have shown damage or have failed.

3. Objectively and clearly identify all possible root causes.

In this case, there has been a mechanical failure of all six lug studs through fatigue. This has been documented by visual and SEM examination of the fracture surfaces. For a comprehensive listing of possible usage-related causes of the stud failure and wheel detachment, the author referenced an instructional pamphlet from the New Zealand Transport agency[4]. The listed "Main Causes of Wheel Loss of Wheel Insecurity" included the following (text is quoted verbatim using British English). After the quoted text, the case analysis is presented in italics.

- Failure to follow manufacturer's instructions for fitting wheels, particularly applicable to after-market products such as aluminum wheels. *Not likely. The correct wheel was used.*

- Failure to tighten wheel nuts to the specified torque, in the correct sequence, or fully tightening the wheel nuts one at a time rather than in stages. *The fatigue failure in a short distance indicates that this failure mode occurred.*

- Failure to retighten wheel nuts after a short period of in-service running (between 50 to 100 kms is commonly recommended). *According to deposition testimony, a re-tightening process was not done.*

- Failure to regularly check tightness of wheel nuts. *This is not applicable as the distance to failure was too short to regularly check the wheel nut tightness.*

- Over-tightening, causing stretched/broken studs or studs to be pulled through the hub. *There is no evidence that this occurred. Since a calibrated torque wrench would reportedly have been used for final tightening, this is an unlikely mechanism.*

- Damaged threads on wheel studs and nuts resulting in insufficient clamping force. *Thread damage to the studs did occur as documented by testing, as the wheel oscillated about the normal travel axis. However, no threads remained on the six accident wheel studs. Thus, there was no evidence to confirm or exclude thread damage causing the eventual fatigue crack initiation.*

- Paint, rust/scale or dirt between contact surfaces of wheels and hubs or nuts. The mating surfaces must be kept clean (and preferably paint-free) to reduce settlement. *This hub was objectionably rusty, but no rustier than the other five hubs on the trailer that did not fail. Thus, corrosion on the hub cannot be a principal cause.*

- Severe corrosion and/or wasting of wheel studs. *The stud remnants were rusty, but no more so than the other corroded studs which did not fail.*

- Damage to the mounting surface of the wheels. *Other than the distorted stud mounting holes, the hub was still serviceable. There is no evidence that pre-existing corrosion damage to the mounting surface of the wheel caused the fatigue failure.*

- Wheel spigot fixing centre 'ground out,' i.e., enlarged. *This was a new wheel, and it does not center via the boss. This wheel centers via the studs. Thus, this mechanism is inapplicable.*

- Incorrect matching of wheel nuts and wheels. (Two-piece flange nuts for hub-mounted wheels and single piece conical seated nuts for stud mounted wheels). *There is no evidence that the nuts at this position were any different than the nuts at any other position that did not fail.*

- Incorrect matching of wheels and wheel hubs (hub mounted and stud mounted). *The accident wheel and hub were functionally identical to those at the other positions. There was no incorrect matching.*

- Incorrect matching of wheel studs and wheel nuts when non-OEM ("aftermarket") wheels have been fitted, reducing the stud length available for correct wheel nut engagement (insufficient "stud standout"). *As the studs were identical across the trailer, and the steel wheel mounting flange / nut seat proportions would all be similar, this is not a likely mechanism.*

- Use of inappropriate (impact tools) or non-calibrated equipment when tightening wheel nuts. *The procedure was correct. That is, it is unobjectionable to use a lower power impact wrench to "snug" the lug nuts prior* *to torquing. The evidence is that this two-step process was not followed.*

4. Objectively evaluate the likelihood of each root cause.

The analysis has been provided in italics above so that each candidate mechanism does not have to be restated.

5. Converge on the most likely root cause.

The evidence indicates that the insufficient torquing of the nuts occurred in this case.

6. Objectively and clearly identify all possible corrective actions.

In the future, the wheel mounting procedure should be validated by taking the trailer for a short trip and then re-torquing each lug nut. This second action will detect lug nuts that were only snugged up, not torqued, and any that have loosened. This is the consensus "best practice" and requires no other alternatives.

7. Objectively evaluate each corrective action.

See ¶ 6.

8. Select the optimal corrective actions.

See ¶ 6.

9. Evaluate the effectiveness of the selected corrective actions.

See ¶ 6.

Summary and Conclusions

For this forensic investigation, the following professional opinions were generated and incorporated into the report given to the client.

- The oncoming driver was blameless.

Basis: He had no reason to expect a wheel and tire to come into his lane, and thus had no reason to take evasive actions. Further, the closing velocity of the tire, a relatively small object, exceeded 100 mph. This is an unexpected event that will occur to few drivers. Perception and reaction times increase when such an unexpected and unfamiliar event occurs.

- The roof strength of the decedent's vehicle was not a contributory cause of the injuries incurred.

Basis: This vehicle has a roof stronger than many of its peers at the time of manufacture. This roof is designed to deal with rollover collisions, not this type of severe, high-velocity impact loading.

- The torque wrench at issue was not a contributory cause of the stud failure and wheel detachment.

Basis: This tool was the correct type of tool; it was in good condition and properly calibrated. None of the other five wheels failed even though this torque wrench was reportedly used before and after the wheel detachment to check torque. The torque wrench could not be contributory if it was not used.

- The wheel, hub, and lug nuts were not defective. Neither those three components nor the pre-existing hub corrosion were contributory causes of the failure of the six studs and resulting wheel detachment.

Basis: The wheel was made of stamped steel, and its weight rating was appropriate to this application. The wheel was damaged in use, but it was not destroyed — that is, it only detached after the last lug stud had fractured. The hub showed no geometric or other defect; the hub deformed rather than fractured when severely loaded by the studs. Note that the corrosion on the hubs was objectionable, but no different than that of the corrosion at the other hub positions that did not fail. These hubs are cast steel and are not made of corrosion-resistant stainless steel; they are designed to still perform safely even with substantial corrosion if the proper pre-load clamping force is applied by the studs.

- The observable remains of the lug studs were non-defective; no material or manufacturing defect of the studs caused the stud failure.

Basis: The studs are appropriate to this application, and identical to the other non-failed studs. They showed no metallurgical defects in microstructure or hardness. Fasteners of this type are expected to fail under severe off-axis loading, which develops fatigue cracks.

- Weather, speed, and roadway conditions were not contributory causes of the stud failure and wheel detachment.

Basis: None of the 30 studs on the remaining five wheels fractured even though they experienced the same weather, speed, and roadway conditions, as did the wheel that failed. In fact, the two remaining wheels on the left side of the trailer endured a more severe loading than did the incident wheel. These two left-hand wheels and studs were driven both to and from the incident location, and they had 50% more loading than did the lead left trailer wheel during the outbound trip.

• The root cause of this wheel detachment was the failure of all six studs on the left front wheel hub of the trailer. This was a fatigue failure caused by insufficient clamping force, which was caused by an insufficient tightening of the lug nuts onto the lug studs.

Basis: The wheel and tire were new and recently installed. Comprehensive metallurgical testing showed no anomaly within the tested six studs. Since no other stud on the trailer failed, there must have been a mounting error. No credible alternative existed other than a lack of clamping force due to insufficiently tightened lug nuts.

• None of the lug nuts at the failed position were properly torqued.

Basis: This wheel suffered "crib death" in that it failed soon after mounting. This type of wheel configuration is highly reliable, and it has an incorporated factor of safety. There is no reason to believe that if only one or two lug nuts had been missed that this wheel position would have failed in fewer than 200 miles.

• This was a preventable failure. Had the lug nuts been re-torqued after a short post-mounting validation trip that followed the servicing of the axles, the error would have been detected and corrected.

Basis: Best practices for tightening lug nuts as well as deposition testimony.

In summary, the default hypothesis (that one of the six sets of lug nuts were untightened) was completely consistent with the evidence. It was particularly likely, given the fact that the wheel was progressively damaged and detached within 150 miles of the maintenance that had been recently performed. However, in any forensic investigation, it is necessary to soberly evaluate contrary opinions. Six candidate explanations for the failure were presented by the opposing expert defending the owner of the trailer, including:

1. The mechanic may not have tightened the left front wheel's lug nuts, and the plaintiff's expert's explanation was correct.

2. Relaxation of the left front wheel's clamp load may be due to the known problem of paint compression after proper wheel lug nut torquing.

3. Potholes and other poor roadway conditions caused wheel to hub slippage, damage, and loss of clamp load after proper wheel lug nut torquing.

4. Although properly installed, the lug nuts were loose due to "an attempted but interrupted theft of the left front tire/wheel" during a stop at a fast food restaurant during the trip.

5. A single wheel stud fractured prematurely and therefore reduced the clamp load and overloaded the other studs, leading to overall failure.

6. The wheel material was not to specification and allowed the relaxation of the clamp load at each of the wheel lug nut positions.

The defense expert pursued none of these explanations and simply presented them as possibilities that diminished the confidence that could be placed in the plaintiff's expert's analysis. He found no evidence either supporting or disconfirming any candidate explanation. Therefore, he had no reason to rule out any explanation or to say that any one of the six candidate explanations was any more likely when compared to any of the other five. His testimony was subjected to legal challenge, and his opinions were excluded as the presiding Circuit Court Judge found the opinions he expressed to be "beyond the scope of his expertise."

The underlying case settled prior to trial.

References

1. Fastener quality act registry, active insignias. http://www.uspto.gov/sites/default/files/FQA_Registry.pdf. July 30, 2015.

2. Oberg E, Jones FD. Machinery's Handbook. South Norwalk (CT): The Industrial Press; 1953.1572-1574.

3. Dennies DP. How to organize and run a failure investigation. Materials Park (OH): ASM International; 2005.

4. New Zealand Transport Agency. Wheel loss information sheet. September, 2010 [date accessed

6/1/2018]. https://nzta.govt.nz/resources/wheel-loss.

Bibliography

Bailey M, Bertoch J. Mechanisms of wheel separations. SAE 2009-01-0111. Warrendale (PA): Society of Automotive Engineers; 2009.

Bickford JH. An introduction to the design and behavior of bolted joints. 1st Edition. New York (NY): Marcel Dekker; 1981.

Camp LS. US District Court, District of Nebraska. Order in case no. 8:10CV111. May 27, 2011.

Hagelthorn GA. Principle modes of failure causing lost wheels from tractor/trailer combination vehicles. SAE 922446. Warrendale (PA): Society of Automotive Engineers; 1992.

Hull D. Fractography. New York (NY): Cambridge University Press; 1999.

Josephs H. Forensic engineering analysis of a pick-up truck wheel-off failure. Journal of the National Academy of Forensic Engineers. Vol. XXIII, No. 2, 2006.

Leffler J. Forensic engineering investigation of vehicle wheel separations. Journal of the National Academy of Forensic Engineers. Vol. XXVI, No. 2, 2009.

Metals handbook Volume 9, Fractography and atlas of fractographs. 8th Edition. Materials Park (OH) American Society of Metals; 1974.

Wheel security – a best practice guide. Kent (England, UK): Freight Transport Association; October, 2009.

Wulpi DJ. Understanding how components fail. 2nd edition. Materials Park (OH): ASM International; 1999.

Forensic Engineering Comparison of Two Masonry Cladding Systems

By Derek A. Hodgin, PE (NAFE 733S)

Abstract

In a recent construction litigation case, there was a disagreement between two qualified engineering experts regarding the technical requirements of a masonry veneer cladding system that was installed on the exterior walls of a residential structure. The disagreement among the experts was related to the classification and function of the veneer cladding system. Specifically, the classification of the cladding system as cast stone or adhered masonry veneer directly impacted the functional requirements set forth by applicable codes and standards. Depending on this classification, the veneer system may or may not be subject to various aspects of the building code, industry standards, and code evaluation reports. The primary areas of concern included the attachment of the panels (i.e., anchored vs. adhered) to the masonry substrate, the extent of water intrusion, and the need for water management details (i.e., flashing and weep holes). Both expert witnesses relied on applicable building codes, industry standards, and manufacturer literature to form their opinions to a "reasonable degree of engineering certainty," yet these technical differences remained. This paper presents the technical highlights of this case study and identifies the issues where building codes and applicable standards require further clarification.

Keywords

Cladding, stone, masonry, adhered, anchored, barrier, drainage, weep, forensic engineering

Introduction

A large oceanfront home was constructed in Myrtle Beach, SC, in 2006. The house was required to be constructed in accordance with the 2003 International Residential Code (IRC 2003). The exterior walls included a combination of cast stone panels and conventional stucco. The cast stone panels were installed on the first floor and on the oceanfront balconies on the second and third floors. The remaining walls were clad with conventional stucco. Cast stone trim panels were used to surround the windows and doors on all three floors. **Figure 1** shows the oceanfront elevation of the subject home.

Shortly after occupancy, the owners observed water intrusion around a third-floor window. After several repair attempts, the water intrusion seemed to stop. However, the water intrusion raised concerns regarding the performance of the exterior walls. An engineering expert retained by the owners determined that the cast stone panels were attached using a combination of thinset-type mortar and carbon steel masonry screws. Additionally, the cast stone did not include flashing or weep holes at wall openings or at the base of the wall. However, the cast stone panels were attached to a back-up wall, consisting of waterproofed concrete masonry units (CMUs).

A lawsuit was filed, claiming that the existing cast

Figure 1
Oceanfront elevation of subject residence.

Derek A. Hodgin, PE, 218 East Main St., Westminster, SC 29693; 864-647-1065; derekhodgin@constructionscience.org

stone veneer should be removed and replaced with a properly constructed stone veneer system in accordance with building code requirements. An engineering expert was retained by the general contractor to review the allegations made in the lawsuit. This paper provides a summary of the testimony provided by the engineering experts and the basis of their testimony.

History of Stone Use

Throughout history, solid stone and solid masonry have been used as a building component on a variety of structures. Many historic structures are constructed either from solid stone or solid masonry. The walls of these structures are load-bearing and are relatively thick. From a building envelope perspective, these walls are referred to as "mass walls," which allow water to penetrate the outer surface, but are so thick that water intrusion to the interior space is not an issue.

As construction technology has evolved, so has the use of solid stone and masonry. The use of stone in modern construction is typically part of a veneer system. By definition, veneer cladding is not load-bearing; it only bears its own weight. Veneer cladding is designed as either a barrier or drainage system. Barrier wall systems are intended to prohibit water intrusion at the exterior surface. In contrast, a drainage wall system is designed with the expectation that incidental water will penetrate the exterior surface, and provisions behind the cladding manage and direct the water back to the exterior.

Definitions

The definitions of cast stone and adhered masonry veneer can be found in the building codes and industry standards. **Figure 2** provides the definitions found in the International Residential Codes (IRC) and the International Building Codes (IBC).

As shown in **Figure 2**, the IRC did not include a definition for adhered masonry veneer until 2009. Additionally, the definition provided in the IRC for adhered masonry veneer is similar to the definition provided in the IBC. The IRC has never included a definition for cast stone. The definitions of cast stone and adhered masonry veneer have not changed in the IBC.

Adhered masonry veneer and cast stone are also defined by industry standards. For example, adhered masonry veneer is defined as a "lightweight, architectural, non-load bearing product that is manufactured by wet cast blending cementitious material, aggregate, iron oxide pigments, and admixtures to simulate the appearance of natural stone" (MVMA 2009). Cast stone is defined as "a refined architectural concrete building unit manufactured to simulate natural cut stone, used in unit masonry applications" (CSI 2011). There are no significant technical differences between these definitions that preclude them from being interchanged.

Building Codes and Standards

The intent of the building code is to provide the design professional and/or general contractor with the minimum requirements to which a building is to be constructed. The building code includes a combination of prescriptive- and performance-based requirements. Prescriptive requirements specifically state how a building is to be constructed, while performance requirements outline a minimum level of building performance.

The IRC provides the minimum requirements for one- and two-family dwellings. Similarly, the IBC provides the minimum requirements for buildings and structures that are not addressed by the IRC. However, it should be noted that the IRC is fully compatible with the IBC. Specifically, the IRC states that "Engineered design in accordance

Building Code	Definitions	
	Adhered Masonry Veneer	Cast Stone
2000 IRC 2003 IRC 2006 IRC	N/A	N/A
2009 IRC 2012 IRC	Stone or masonry veneer secured and supported through the adhesion of an approved bonding material applied to an approved backing.	
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	Veneer secured and supported through the adhesion of an approved bonding material applied to an approved backing.	A building stone manufactured from Portland cement concrete precast and used as a trim, veneer or facing on or in buildings or structures.

Figure 2
Summary of IBC and IRC definitions.

with the International Building Code is permitted for all buildings and structures, and parts thereof, included in the scope of this code" (IRC 2003). As described earlier, the IBC has provided definitions for adhered masonry veneer and cast stone, while the IRC only recently introduced a definition for adhered masonry veneer.

Additionally, the Building Code Requirements for Masonry Structures ACI 530-02/ASCE 5-02/TMS 402-02 (ACI 530) is the code-referenced standard for masonry structures referenced in the 2003 IBC. Other relevant standards are considered to represent a non-mandatory "best practices" guide. Therefore, the engineering experts for the litigation case study relied on the requirements provided in the 2003 IBC and ACI 530.

International Building Code

Typically, building codes and standards are changed and modified as construction technology has evolved. However, there have been very few changes to adhered masonry veneer requirements in the building codes and industry standards. A summary of the changes in the IBC requirements regarding adhered masonry veneer is provided in **Figure 3**.

As shown in **Figure 3**, few changes or modifications to the code requirements for adhered masonry veneer took place between the 2000 IBC and 2009 IBC. The building code essentially relies on the requirements set forth by ACI 530 for adhered masonry veneer. Additional requirements were added to the adhered masonry veneer section of the 2012 IBC.

The IBC also includes water management requirements to prevent incidental water from penetrating the building envelope. Specifically, the IBC requires that

Building Code	Code Section	Building Code Requirement
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	1405.9 1405.9 1405.9 1405.10 1405.10	Adhered masonry veneer shall comply with the applicable requirements of Section [varies] and Section 6.1 and 6.3 of ACI 530/ASCE 5/TMS 402.
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	1405.9.1 —— —— —— ——	Adhesion developed between adhered veneer units and backing shall have a shear strength of at 50 pounds per square inch (0.34 Mpa) based on gross unit surface area or shall be adhered in compliance with Article 3.3C of ACI 530.1/ASCE 6/TMS 602.
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	—— —— —— —— 1405.10.1	Exterior adhered masonry veneer shall be installed in accordance with Section 1405.10 and in accordance with the manufacturer's instructions.
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	—— —— —— —— 1405.10.1.1	Water-resistive barriers shall be installed as required in Section 2510.6.
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	—— —— —— —— 1405.10.1.2	A corrosion-resistant screed or flashing of a minimum 0.019-inch (0.48 mm) or 26 gauge galvanized or plastic with a minimum vertical attachment flange of 3 1/2 inches (89 mm) shall be installed to extend a minimum of 1 inch (25 mm) below the foundation plate line on exterior stud walls in accordance with Section 1405.4. The water-resistive barrier shall lap over the exterior of the attachment flange of the screed or flashing.
2000 IBC 2003 IBC 2006 IBC 2009 IBC 2012 IBC	—— —— —— —— 1405.10.1.3	On exterior stud walls, adhered masonry veneer shall be installed a minimum of 4 inches (102 mm) above the earth, or a minimum of 2 inches (51 mm) above paved areas, or a minimum of 1/2 inch (12 mm) above exterior walking surface which are supported by the same foundation that supports the exterior wall.

Figure 3
Summary of IBC requirements for adhered masonry veneer.

Building Code	Siding Material	Water-Resistive Barrier Required	Type of Supports for Siding Material and Fasteners	Footnotes
2000 IRC	Brick Veneer, Concrete Masonry Veneer	Yes	See Section R703 and Figure R703.7	(h) All attachments shall be coated with a corrosion-resistant coating
2003 IRC	Brick Veneer, Concrete Masonry Veneer	Yes	See Section R703 and Figure R703.7	(h) All attachments shall be coated with a corrosion-resistant coating
2006 IRC	Brick Veneer, Concrete Masonry Veneer	Yes	See Section R703 and Figure R703.7	(g) All attachments shall be coated with a corrosion-resistant coating (z) Adhered masonry veneer shall comply with the requirements of Section R703.6.3 and shall comply with the requirements in Section 6.1 and 6.3 of ACI 530/ASCE 5/TMS-402
2009 IRC	Adhered Veneer: Concrete, Stone or Masonry	Yes	See Section R703.6.1 or in accordance with the manufacturer's instructions	(g) All attachments shall be coated with a corrosion-resistant coating (w) Adhered masonry veneer shall comply with the requirements of Section R703.6.3 and shall comply with the requirements in Section 6.1 and 6.3 of ACI 530/ASCE 5/TMS-402
2012 IRC	Adhered Veneer: Concrete, Stone or Masonry	Yes	See Section R703.6.1 or in accordance with the manufacturer's instructions	(g) All attachments shall be coated with a corrosion-resistant coating (w) Adhered masonry veneer shall comply with the requirements of Section R703.6.3 and shall comply with the requirements in Section 6.1 and 6.3 of ACI 530/ASCE 5/TMS-402
Note: Only selective portions of Table R703.4 are shown above for reference.				

Figure 4
Summary of IRC Table R703.4 requirements for masonry veneer.

flashing be installed around penetrations (i.e., windows and doors), terminations, intersections and locations where moisture could penetrate the building envelope. The flashing has to allow any incidental water to exit the building envelope. Since the earliest IBC, the same provisions for water management, with minor modifications, have been required.

International Residential Code

Similar to that of the IBC, the International Residential Code (IRC) includes the minimum requirements to which a residential home is to be constructed. The minimum requirements for the attachment of adhered masonry veneer are covered in Table R703.4 "Weather-Resistant Siding Attachment and Minimum Thickness" of the IRC codes [2000 through 2012 editions]. Similar to the IBC, few changes and modifications regarding the attachment of the adhered masonry veneer have been made (**Figure 4**).

As shown in **Figure 4**, beginning in the 2006 IRC, the ACI 530 is referenced by the footnotes of Table R703.4. Additionally, manufacturer installation instructions began to be referenced in the 2009 IRC.

Similar to the IBC, the IRC provides water management requirements for the building envelope. Since the first IRC in 2000, flashing has been required to prevent the entry of water into the building envelope. If incidental water penetrates through the building envelope, then the flashing must allow the water to exit. The flashing should be installed around penetrations in the building envelope (i.e., windows and doors).

ACI 530/ASCE 5/TMS 402

Similar to that of the IBC and IRC codes, the requirements set forth in the ACI 530 have seen few changes and modifications. **Figure 5** shows the minor changes or modifications with regard to the various editions of ACI 530 referenced by the IBC building code and later IRC codes.

As shown in **Figure 5**, there has been only one modification between the 2000 IBC and 2012 IBC. Specifically, Section 6.3.2.4 required that the adhesion developed between the adhered masonry veneer and backing wall

Building Code	Standard	Section	Standard Requirement
2000 IRC 2003 IRC 2006 IRC 2009 IRC 2012 IRC	ACI 530-99/ASCE 5-99/TMS 402-99 ACI 530-02/ASCE 5-02/TMS 402-02 ACI 530-05/ASCE 5-05/TMS 402-05 ACI 530-08/ASCE 5-08/TMS 402-08 ACI 530-11/ASCE 5-11/TMS 402-11	6.1.2.1 6.1.5.1 6.1.5.1 6.1.5.1 6.1.6.1	Design and detail the backing system of exterior veneer to resist water penetration. Exterior sheathing shall be covered with a water-resistant membrane unless the sheathing is water resistant and the joints are sealed.
2000 IRC 2003 IRC 2006 IRC 2009 IRC 2012 IRC	ACI 530-99/ASCE 5-99/TMS 402-99 ACI 530-02/ASCE 5-02/TMS 402-02 ACI 530-05/ASCE 5-05/TMS 402-05 ACI 530-08/ASCE 5-08/TMS 402-08 ACI 530-11/ASCE 5-11/TMS 402-11	6.3.2.1	Adhered veneer units shall not exceed $2^5/_8$ inches (66.7 mm) in specified thickness, 36 inches (914 mm) in any face dimension, nor more that 5 ft^2 (0.46 m^2) in total face area, and shall not weight more than 15 lbs/ft^2 (718 PA).
2000 IRC 2003 IRC 2006 IRC 2009 IRC 2012 IRC	ACI 530-99/ASCE 5-99/TMS 402-99 ACI 530-02/ASCE 5-02/TMS 402-02 ACI 530-05/ASCE 5-05/TMS 402-05 ACI 530-08/ASCE 5-08/TMS 402-08 ACI 530-11/ASCE 5-11/TMS 402-11	6.3.2.3	Backing shall provide a continuous, moisture-resistant surface to receive the adhered veneer. Backing is permitted to be masonry or concrete, or steel or wood framing with metal lath and portland cement plaster.
2000 IRC 2003 IRC 2006 IRC 2009 IRC 2012 IRC	ACI 530-99/ASCE 5-99/TMS 402-99 ACI 530-02/ASCE 5-02/TMS 402-02 ACI 530-05/ASCE 5-05/TMS 402-05 ACI 530-08/ASCE 5-08/TMS 402-08 ACI 530-11/ASCE 5-11/TMS 402-11	6.3.2.4	Adhesion developed between adhered veneer units and backing shall have a shear strength of at least 50 psi (345 kPa) based on gross unit surface area (when tested in accordance with ASTM C 482)*, or shall be adhered in compliance with Article 3.3 C of ACI 530.1/ASCE 6/TMS 602.
Note: Additional requirement included in the ACI 530/ASCE 5/TMS 402 2005, 2008 and 2011.			

Figure 5
Summary of ACI 530 / ASCE 5 / TMS 402 requirements.

be tested in accordance with ASTM C482. This modification was initially included in the 2005 edition of ACI 530 (IBC 2006).

There are two ways to design the adhered masonry veneer using the ACI 530. Specifically, the design professional can design the adhered masonry veneer using the prescriptive requirements or use the alternative design requirements. These design methods are described in Chapter 6 of ACI 530, which addresses masonry veneer. The design professional is allowed to use the alternative design method if certain conditions are met. Most importantly, the alternate design must meet the general design requirements regarding flashing and weep holes.

Masonry Veneer Manufacturers Association

The Masonry Veneer Manufacturers Association (MVMA) is an industry group that has published installation guidelines for Adhered Concrete Masonry Veneer (ACMV). However, the MVMA is not referenced in the building codes. Therefore, the MVMA guidelines are considered a non-mandatory "best practices" guide. According to the MVMA, flashing is required for adhered masonry veneer systems. Specifically, "all flashing and flashing accessories must be corrosion resistant materials and integrated with the WRB materials. Flashing must be installed at all through wall penetrations and at terminations of ACMV installation" (MVMA 2009).

Case Study

As previously introduced, the subject oceanfront residence in this case study was constructed in Myrtle Beach, SC, in 2006. The applicable building code was the 2003 IRC. The exterior walls of the subject residence were clad with a combination of cast stone panels and conventional stucco. The cast stone panels were installed on the first floor and on the oceanfront balconies on the second and third floors (**Figure 6** and **Figure 7**). The remaining walls were clad with conventional stucco. Cast stone trim panels

Figure 6
Cast stone panels installed on first floor.

Figure 7
Vertical face of rear balconies.

were installed around the windows and doors on all three floors.

The size of the typical cast stone panels was measured to be approximately 24 inches by 36 inches and one inch in thickness. Custom cast stone panels were noted to have dimensions greater than 36 inches in some areas. The cast stone panels were adhered using thinset-type mortar over a waterproofed CMU wall. In some instances, the cast stone panels were observed to be attached to the exterior walls with a combination of thinset-type mortar and carbon steel masonry screws (**Figure 8** and **Figure 9**). The thinset mortar did not cover the entire backside of the cast stone panels. It was installed using the "spot bonding" method. The spot bonding method is where the mortar provides only partial coverage of the cast stone panel (Goldberg 1998). The cast stone veneer did not include flashing or weep holes at wall openings or at the base of the wall. However, the liquid-applied waterproofing was believed to turn into the wall openings.

Comparison of Engineering Opinions /Recommendations

The engineering experts had differing opinions regarding the as-built exterior cladding system installed at the subject residence. Specifically, the primary areas of concern and disagreement included the attachment of the cast stone panels to the masonry substrate and the need for water management details. Because of these differences, the recommended repair scopes were also different. A summary of the opinions offered, including the technical references cited by the plaintiff and defense experts, is provided below.

Cast Stone Panel Attachment

The primary method of attachment for the subject cast stone veneer units was adhesion via thinset-type mortar installed in a "spot bonding" method, supplemented by the installation of steel masonry screws. In Goldberg's *Technical Design Manual for Direct Adhered Ceramic Tile, Stone and Thin Brick Facades*, he describes limitations of the "spot bonding" method of attachment (Goldberg 1998). Specifically, the following "important principles" are outlined for the architect and contractor to consider:

- Spot bonding is only suitable when using adhesives with very high bonding strength and flexibility, such as new technology epoxies and structural silicone, and may require supplemental mechanical anchorage.

- Spot bonding should not be used in wet climates

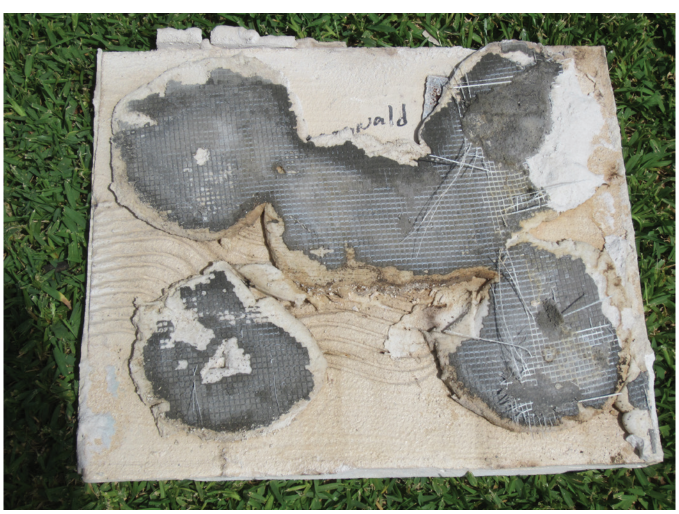


Figure 8
"Spot bonding" on backside of cast stone panel.

Figure 9
Masonry screw used to attach a cast stone panel.

with cladding materials that have high water absorption or water sensitivity.

- Back-up wall construction must make provision for waterproofing and flashing the cavity between the substrate and the cladding surface.

- Spot bonding may not be suitable for extreme climates or conditions (Goldberg 1998).

Summary of Cast Stone Attachment Opinions

Plaintiff Expert

- The code evaluation report for steel masonry screws did not allow for exterior use.

- The "spot bonding" adhesion method is not recommended for the coastal environmental (Goldberg 1998).

- The "spot bonding" adhesion method is inconsistent with code requirements and accepted standards that adhesive should "be forced out between the edges of the veneer units" (ACI 530-99/ASCE 5-99/TMS 402-99).

- The observed "spot bonding" pattern was noted to cover approximately 50 to 60 percent of the veneer surface, less than 95 percent described by an industry reference (Goldberg 1998).

- The presence of waterproofing over the CMU wall, and the absence of data from component manufacturers stating otherwise, precludes the use of an adhered attachment method (MVMA 2009).

Defense Expert

- The veneer is not cast stone, but is an adhered masonry veneer.

- The code evaluation report for the steel masonry screws did not allow for exterior use, but the steel masonry screws were used for temporary attachment while the thinset mortar cured.

- The "spot bonding" adhesion method is sufficient for the coastal environmental.

- The "spot bonding" adhesion method is inconsistent with code requirements and accepted standards, but provides sufficient adhesion for the intended use.

- The presence of waterproofing over the CMU wall does not compromise the adhesion of the veneer units such that a repair is warranted.

Discussion of Cast Stone Attachment Issues

Plaintiff Expert

- The cast stone veneer units were easily removed from the exterior wall assembly during destructive testing using a grinder to remove perimeter mortar joints and applying prying action with hand tools at the edge of the panel.

- The adhesive covered approximately 50 to 60 percent of the veneer surface.

- The adhesive failure occurred between the adhesive and the unidentified liquid-applied waterproofing product installed on the exterior surface of the CMU.

- The water intrusion that occurred during the short service life of the subject structure had resulted in localized areas of efflorescence.

- The water intrusion that occurred during the short service life of the subject structure had resulted in corrosion of the steel masonry screws.

Defense Expert

- The veneer units required significant effort to be removed from the exterior wall assembly during destructive testing. The use of a grinder to remove perimeter mortar joints and applying prying action with hand tools at the edge of the panel would exceed the code-prescribed loads that the veneer is required to resist.

- The adhesive covered a sufficient area of the veneer surface to resist code-prescribed loads. Additionally, no meaningful tests were performed by the plaintiff to prove otherwise.

- The water migration that occurred during the short service life of the subject structure had resulted in localized areas of efflorescence. However, these areas were limited and resulted in cosmetic issues only. The thinset mortar is not susceptible to moisture-related degradation.

- The water intrusion that occurred during the short service life of the subject structure had resulted in corrosion of the steel masonry screws. However, these screws were installed for temporary support of the veneer units while the adhesive mortar was setting. Therefore, these screws are unnecessary and because their continued presence may cause aesthetic rust spots, they should be removed.

Water Management Details

The subject stone cladding did not include effective water management details. While the waterproofing of the CMU backup wall should preclude water intrusion to the interior of the home, water was able to migrate in and out of the mortar joints surrounding the stone, collect in the air space behind the stone, corrode the steel masonry screws used for attachment, and cause efflorescence on the exterior wall surfaces.

Summary of Water Management Opinions

Plaintiff Expert

- The subject wall is constructed as a drainage wall and should have included flashing and weepholes at wall openings and at the base of the wall (IRC 2003) (ACI 530-99).

- The presence of mortar joints around the cast stone units allows incidental water to penetrate the wall assembly.

- The water intrusion has caused efflorescence on the exterior surfaces of the cast stone units.

- The water intrusion, and the presence of efflorescence, serve to compromise the adhesive bond between the cast stone veneer and the waterproofed CMU wall (Goldberg 1998).

- The water intrusion, and the presence of efflorescence, serve to compromise the adhesive bond between the cast stone veneer and the waterproofed CMU wall (Goldberg 1998).

Defense Expert

- The subject wall is constructed as a mass or barrier wall such that flashing and weepholes are not required.

- The presence of mortar joints around the adhered masonry veneer units does not allow sufficient water to penetrate the wall assembly to cause a problem that warrants repair.

- Incidental water migration inboard of the veneer has caused efflorescence on the exterior surfaces of the veneer in localized areas, but this condition is cosmetic and does not warrant a wholesale repair.

- The incidental water migration between the veneer and CMU wall, and the presence of efflorescence in localized areas, was not been shown to compromise the adhesive bond between the veneer and the waterproofed CMU wall.

Discussion of Water Management Issues

Plaintiff Expert

- The project plans called for the installation of flashing and weeps around the windows.

- The project specifications call for a moisture barrier of Portland Cement with an expanded galvanized metal lath.

- The applicable building code (IRC 2003) and recognized industry standards requires exterior walls to provide weather-resistance. This is typically accomplished by exterior cladding that includes flashing designed to allow the accumulation of incidental water that may get behind the exterior cladding to exit.

- The exterior cladding system is not a monolithic system (i.e., one solid precast panel) and was constructed with mortar joints between adjacent precast panels. Mortar is considered a porous material; therefore, water is able to migrate through the mortar joints and get behind the precast panels.

- A waterproofing membrane was installed over the CMU backing wall. The waterproofing membrane prevents incidental water to penetrate through the CMU backing wall. However, this incidental water requires an exit via flashing and weepholes so that water is not accumulated within the wall assembly.

Defense Expert

- The existing cladding system at the subject residence is an adhered masonry veneer installed onto a CMU backing wall. As such, the 2003 IBC exempts flashing, water-resistive barrier and a drainage plane when the exterior walls are constructed with concrete or CMU. The waterproofing membrane on the face of the CMU is a back-up measure to prevent incidental water from penetrating the CMU.

- The water-resistant effectiveness of the barrier wall systems is proven by the lack of water intrusion through the wall system to the interior.

- Typical manufacturers of adhered masonry veneer do not require a drainage system behind the adhered masonry veneer system on a CMU wall. The flashing weephole and drainage provisions are intended for a wood or steel framed cavity wall system susceptible to water-related damage.

Recommended Repair Scope

Based on the differing interpretations described above, the recommended repair scopes submitted by the plaintiff and defense experts were substantially different. A summary of the repair scopes is shown below.

Plaintiff Expert

- The existing cast stone veneer system requires complete removal and replacement to address attachment and water management issues.

- Removal and replacement of cast stone veneer will include the installation of metal lath to accomplish attachment of the new adhered veneer system.

- Flashing and weepholes will be installed at wall openings (i.e., windows and doors) and at the base of the wall.

Defense Expert

- The existing steel masonry screws should be removed from the existing cast stone veneer units.

Conclusions / Recommendations

This case study highlights the conflicting requirements for masonry veneer as described by building codes, code-referenced standards, and industry standards. The conflicting requirements appear to be based entirely on how a cladding system is classified, rather than how it functions. For this reason, it may be possible to construct a "code-compliant" wall that fails to provide long-term function and/or adequate performance.

Codes and standards should be revised to reflect the current knowledge base regarding the function of masonry wall assemblies. Less focus should be given to how a wall system is identified or how the individual components are defined. The author's attempt to classify various types of walls and provide prescriptive requirements resulted in conflicting interpretations when the wall does not specifically "fit" one description and/or definition.

While it appears that some changes have been made to more recent codes and standards (that post-date the case study described by this paper), additional work is needed to clarify the details necessary for a functional and durable stone veneer system. The author recommends that unless a stone cladding system is installed as a true barrier system, adequate water management features should be included. When incidental water penetration is possible, these features should serve to protect the underlying substrate and manage the water in a manner that does not compromise the structural (i.e., attachment) or aesthetic integrity of the wall system.

All exterior cladding systems that include mortar joints should include water management details to address incidental water that enters the wall assembly. Building codes have slowly improved by recognizing that water management details are needed to protect the wall assembly itself, not just the occupied interior space. However, industry standards, manufacturer installation instructions and design professionals need to follow suit by providing details that not only comply with the building code, but also provide long-term durability and function.

References

ACI 530-1999. Building code requirements for masonry structures: ACI 530-99/ASCE 5-99/TMS 402-99. The Masonry Standards Joint Committee.

ACI 530-2002. Building Code Requirements for Masonry Structures: ACI 530-02/ASCE 5-02/TMS 402-02. The Masonry Standards Joint Committee.

ACI 530-2005. Building Code Requirements for Masonry Structures: ACI 530-05/ASCE 5-05/TMS 402-05. The Masonry Standards Joint Committee.

ACI 530-2008. Building Code Requirements for Masonry Structures: ACI 530-08/ASCE 5-08/TMS 402-08. The Masonry Standards Joint Committee.

ACI 530-2011. Building Code Requirements for Masonry Structures: ACI 530-11/ASCE 5-11/TMS 402-11. The Masonry Standards Joint Committee.

ASTM C482-2002(r2014). Standard Test Method for Bond Strength of Ceramic Tile to Portland Cement Paste, West Conshohocken (PA). ASTM International.

Cast Stone Institute. Technical manual with case histories. Lebanon (PA): Cast Stone Institute; 2011. pg. 2.

Goldberg RP. Direct adhered ceramic tile, stone and thin brick facades – Technical design manual. Bethany (CT): Laticrete International, Inc.; 1998.

IBC 2000. 2000 International Building Code. Falls Church (VA): International Code Council, Inc.

IBC 2003. 2003 International Building Code. Country Club Hills (IL): International Code Council, Inc.

IBC 2006. 2006 International Building Code. Country Club Hills (IL): International Code Council, Inc.

IBC 2009. 2009 International Building Code. Country Club Hills (IL): International Code Council, Inc.

IBC 2012. 2012 International Building Code. Country Club Hills (IL): International Code Council, Inc.

IRC 2000. 2000 International Residential Code for One- and Two-Family Dwellings. Falls Church (VA): International Code Council, Inc.

IRC 2003. 2003 International Residential Code for One- and Two-Family Dwellings. Country Club Hills (IL): International Code Council, Inc.

IRC 2006. 2006 International Residential Code for One- and Two-Family Dwellings. Country Club Hills (IL): International Code Council, Inc.

IRC 2009. 2009 International Residential Code for One- and Two-Family Dwellings. Country Club Hills (IL): International Code Council, Inc.

IRC 2012. 2012 International Residential Code for One- and Two-Family Dwellings. Country Club Hills (IL): International Code Council, Inc.

Masonry Veneer Manufacturers Association. Installation guidelines for adhered concrete masonry veneer. Washington (DC): Masonry Veneer Manufacturers Association; 2009. pp. 3, 8.