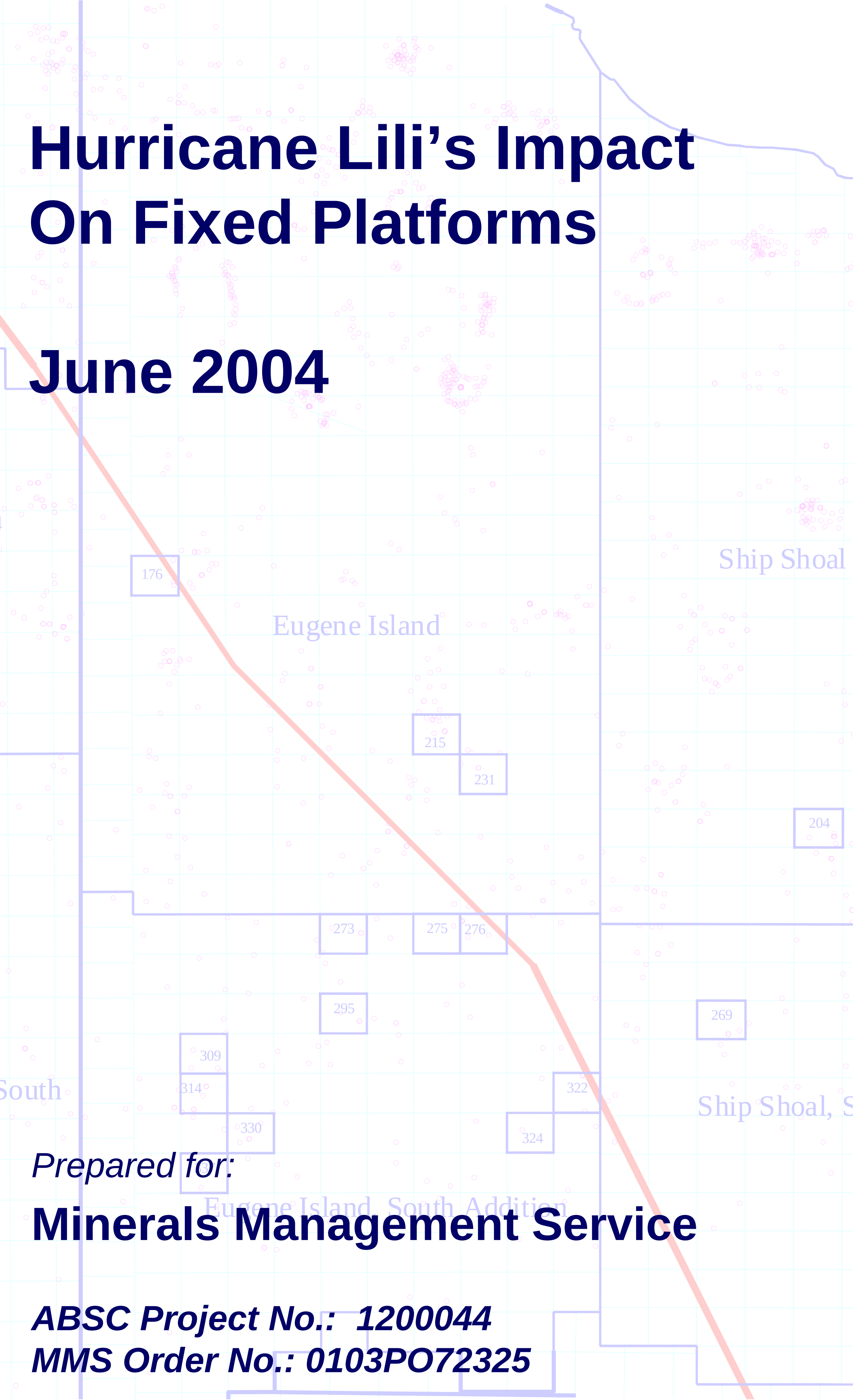
Hurricane Lili's Impact On Fixed Platforms

June 2004



Prepared for:

Minerals Management Service

ABSC Project No.: 1200044
MMS Order No.: 0103PO72325

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RISK CONSULTING DIVISION

EQE
INTERNATIONAL

Table of Contents

Executive Summary

Background

When hurricane Lili passed through a region of fixed offshore platforms in September 2003, it provided an opportunity to better understand the performance of fixed based platforms in extreme hurricanes. While a large majority of fixed platforms performed adequately during Lili with no damage reported, a smaller set were damaged significantly and in several cases the platforms collapsed. Extreme hurricanes such as Lili that pass through an area of densely populated offshore platforms are rare. The last such event was hurricane Andrew in 1992 that damaged and failed several platforms. Several studies conducted following Andrew resulted in several lessons learned and updates to the offshore industries platform design and assessment approaches.

Based upon this background, the Minerals Management Service (MMS) funded a study to investigate the performance of fixed jackets during Lili. The study is documented in this report. There were two parts to the study. The first was a *qualitative* assessment of platform performance that documents the general nature of the platform survival, damage and failures. The second was a *quantitative* assessment that used probabilistic techniques to determine how several platforms actually performed in Lili (i.e., survived, damaged, or failed) compared to what the API RP 2A standard for fixed platform design would have predicted using analytical techniques.

Qualitative Assessment

The first part of the study gathered data on the general impact of Lili on offshore fixed platforms in terms of survival, damage and collapse of platforms. The main focus is a descriptive summary, including photos, of the types of global platform damage and local component damage caused by Lili. This part of the report is intended to provide a lasting record of the effects of Lili on fixed platforms.

Specific findings and trends were summarized related to global platform performance as well as component performance. Table E.1 shows a list of the 17 platforms with significant damage or failures during Lili. Several of the key observations of platform performance include:

- **Age is the Critical factor in Determining Platform Performance.** As with prior hurricanes, age was again determined to be the biggest factor in platform performance.

Fourteen of the significantly damaged platforms were installed prior to 1980. Platforms in this era were designed when API RP 2A was still evolving and often had lower decks, smaller members and weaker joints than post-1980 platforms. These findings are consistent with those from Andrew.

- **Platforms with Low Decks are at the Greatest Risk of Failure in Hurricanes.** Several of the pre-1980 platforms were known to have low decks and likely failed due to the large forces exerted on a platform should an extreme wave crest hit the deck structure. Low decks are a result of the smaller wave criteria used at the time the platform was installed. Platforms with low decks are at a much greater risk of failure during hurricanes. This was also demonstrated in Andrew.
- **MMS Mandated Underwater Inspections Revealed Additional Platform Damage.** In January 2003 the MMS issued Notice to Lessees (NTL) No.: 2003-G04 which required subsea inspections for platforms along the path of highest waves during Lili. Such a "Special Survey" following an extreme event is also recommended in API RP 2A. Following these underwater inspections, seven additional platforms were identified with significant damage that had not been apparent immediately following the storm, These platforms are shaded gray in Table E.1 and represent almost one half of all the platform damage. This demonstrates the usefulness of this type of Special Survey.
- **Concentration of an Operator's Platforms in a Single Location.** The tendency for operators to have a large number of platforms grouped together in a relatively small geographical area is useful for operational considerations. However, since hurricanes tend to directly impact a relatively narrow band, multiple platforms in an operator's fleet can be put at risk from a single event. As an example, one operator had over 70 platforms experience damage in Lili. Although the damage to each platform was mostly minor, the cumulative effect was significant. Operators should consider diversity in their platform fleet locations so that they are not significantly impacted by a single event.
- **The Usefulness of API RP 2A Section 17 was Demonstrated.** This guideline provides operators and the MMS with a methodology for reassessing existing platforms. Prior to Lili, several platforms had used the Section 17 approach to upgrade a platform, or alternatively, determine that it was not economical to make the upgrade. In one case, the operator decided to strengthen the platform and as expected, it survived Lili. In the second case, the operator decided that the platform could not economically be strengthened, so it reduced production and was in the process of abandoning the platform when Lili hit and the platform failed. In both cases, Section 17 provided the operator for a framework for making the proper decision.
- **The Cost of Platform Damage and Cleanup can be Significant.** In order to maintain a safe work environment and provide protection for the environment, novel and sometimes, expensive methods are required to safely decommission a platform that has been damaged in a storm. Primary considerations for these decommissioning operations are removing production facilities from the topsides, permanently plugging and abandoning the operating wells, and disposing of the jacket structure through removal or reefing operations. This process for one of the platforms damaged in Lili took approximately one year to implement and cost tens of millions of dollars. Operators should consider the potential cost of platform failures in their economic decision processes.

Table E.1. Platforms with Significant Damage Resulting From Hurricane Lili

Area	Block	Description of Platform and Damage
EI	176	Installed in 1958 in 80 feet of water. Damage to skirt pile framing (cracks) necessitated the removal of this platform. This damage could only be detected by underwater survey.
EI	215	Installed in 1983 in 98 feet of water. Damage includes a visible lateral deformation and the platform was removed.
EI	231a	Installed in 1968 in 111 feet of water. Damage includes a visible lateral deformation and the platform was removed.
EI	231b	Installed in 1971 in 106 feet of water. Heavy damage was visible without underwater survey.
EI	273	Installed in 1970 in 191 feet of water. Underwater survey post-Lili identified four damaged k-nodes in the transverse framing rows. Also impact damage to a vertical diagonal was identified. Clamp repairs were used to repair the platform.
EI	275	Installed in 1964 in 172 feet of water. This platform was destroyed (toppled) by Hurricane Lili.
EI	276	Installed in 1971 in 172 feet of water. Post-Lili underwater survey identified damage to a vertical diagonal through the splash zone and leg severance near El. (-) 22'. This damage was repaired by member replacement and leg grouting.
EI	295	Installed in 1972 in 211 feet of water. Evidence indicated a wave crest 5 feet above the cellar deck during Hurricane Lili. Damage to the jacket includes a severed leg, damaged k-node and three damaged vertical diagonals all in the same vertical row near El. (-) 33'. This platform was abandoned.
EI	309	Installed in 1969 in 218 feet of water. This platform was completely destroyed by Hurricane Lili.
EI	314	Installed in 1973 in 235 feet of water. A boat landing became detached during the storm and its fall collapsed some vertical diagonal braces. This damage could only be detected by underwater survey.
EI	322	Installed in 1978 in 235 feet of water. It is believed that a fabrication flaw associated with the piles ed to the platform failure o. This led to severe damage to the platform which was later stabilized allowing decommissioning and removal.
EI	324	Installed in 1990 in 260 feet of water. MMS indicated that the platform damage was severe enough to require removal.
EI	330a	Installed in 1971 in 244 feet of water. Post-Lili underwater survey identified heavy damage.
EI	330b	Installed in 1971 in 248 feet of water. Post-Lili underwater survey identified heavy damage.
EI	337	Installed in 1982 in 268 feet of water. Post-Lili underwater survey identified heavy damage.
SS	204	Installed in 1968 in 100 feet of water. Post-Lili underwater survey identified crack indications in conductor guide framing members at the (-) 25' elevation.
SS	269	Installed in 1965 in 170 feet of water. Post-Lili survey identified 8 broken or missing vertical diagonal members through the splash zone.

Note: Damage to platforms shown in gray was located via underwater inspection.

Quantitative Assessment

The second part of the study involved a comparison of the expected performance of platforms in Lili based upon API RP 2A analytical approaches, to the actual observed performance (platform survived, was damaged or failed). The approach used a probabilistic "Bayesian" process that was the same as that used for a similar comparison performed following Andrew.

The result of the comparison process is a *bias factor* that reflects how well API RP 2A predicts platform behavior under extreme loads. A bias factor of 1 means that the API analytical process exactly predicts the observed performance of platforms in hurricanes, That is, it predicts if they will survive, be damaged, or fail. A bias factor of less than one (e.g., 0.9) means that the API RP 2A process is *unconservative* and underestimates actual platform performance (in this example, by about 10 percent). A bias factor of more than one means that the analytical process is conservative and overestimates actual performance. A bias factor of greater than 1 is preferred, since it means that AP RP 2A has built-in conservatism.

Note that in determining the bias factors, all of the known safety factors contained in API RP 2A were accounted for in the process. For example, safety factors associated with allowable bending and axial loads as well as the use of nominal steel strength. Hence the bias factor determined here reflects unknown conservatism in the process.

Figure E.1 shows the overall results of the evaluation in terms of the bias factor computed for Lili, Andrew and for the combination of the two. The center of each distribution is the approximate value of the mean bias factor, which was approximately 1.2 for Lili and 1.1 for Andrew – both reflecting that API RP 2A is doing a good, conservative job of estimating platform performance, with conservatism in the range of 10 to 20 percent. Also shown is a combined curve where the results of this evaluation for Lili were combined with the 1994 evaluation of Andrew, resulting in a bias factor of a little less than 1.2 (note that these comparisons are nonlinear and cannot just simply be added and averaged). In conclusion, the API RP 2A approach provides for well designed platforms in terms of response to hurricanes as determined by analytical studies for both Lili and Andrew.

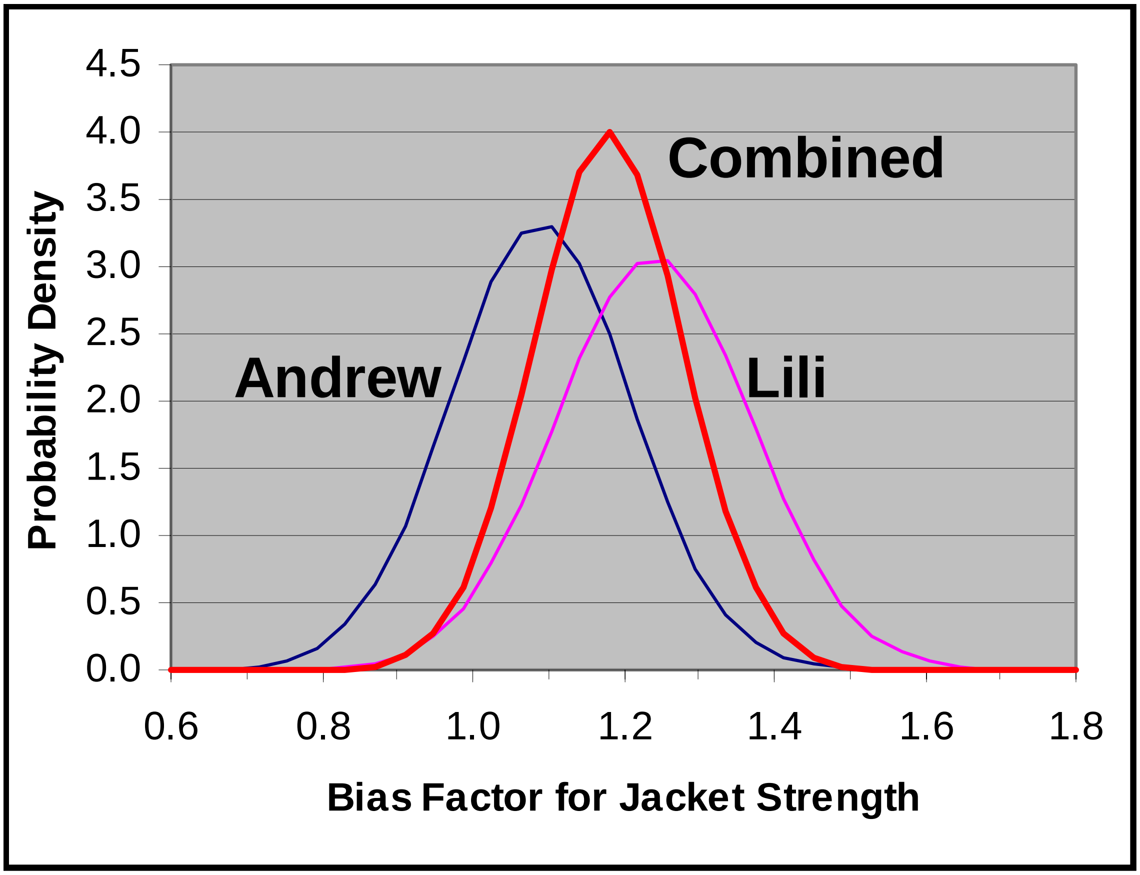

Figure E.1 – Bias Curves for Andrew, Lili and Combined.
The mean value of the bias factor is at approximately the center of the distribution.

1.0 Background

1.1 Hurricane Andrew Fixed Platform Study

In 1992, Hurricane Andrew damaged numerous offshore platforms in the Gulf of Mexico, causing several to collapse. This presented a unique opportunity to "test" the API RP 2A design process by comparing platforms that survived, were damaged, or failed in hurricane Andrew against what API RP 2A would have predicted. A Joint Industry Project (JIP) was initiated that developed and implemented a probabilistic comparison process based on Bayesian updating. The process indicated that the API RP 2A design approach results in a conservative platform design with about 10 to 20 percent margin -- prior to the application of factors of safety. With the normal factors of safety included, the conservatism would be much higher. The Andrew JIP was funded by over 20 organizations including the Minerals Management Service (MMS). There were two phases of the JIP as described in References 1, 2 and 3.

Hurricane Andrew provided a good sample for the comparison process. However, one of the limiting factors was that only 13 platforms were used. Also, many of the platforms were in the same vicinity (South Timbalier), and of similar design (old Gulf Oil).

Also at that time, API was in the process of developing API RP 2A Section 17, which establishes a procedure for the assessment of existing platforms. The Andrew JIP was used by the API Section 17 Task Group to help test and calibrate the Section 17 process for assessment of existing platforms.

1.2 Hurricane Lili Fixed Platform Study

In 2002, Hurricane Lili damaged several platforms, including a few that were a complete loss. This provided a similar opportunity as Hurricane Andrew had to further study the API process and update the Andrew comparison with new platforms – particularly those of different location and design. Based on this background, the MMS funded ABS Consulting to perform a study of the performance of fixed platforms during Lili. The study is reported in detail within this document. A summary of the work was also presented at the Offshore Technology Conference (OTC) in 2004, and is contained in Appendix B.

1.3 Scope of Study

This study is divided into two main parts.

The first part of the study gathered data on the general impact of Lili on offshore fixed platforms in terms of survival, damage and collapse of platforms. The main focus is a descriptive summary, including photos, of the types of global platform damage and local component damage caused by Lili. This part of the report is intended to provide a lasting record of the effects of Lili on fixed platforms. Specific findings and trends were summarized related to global platform performance as well as component performance.

The second part of the study involved a probabilistic-based comparison of the expected performance of platforms in Lili based on API RP 2A analytical approaches to the actual observed performance (i.e., platform survived, was damaged or failed). The probabilistic approach was the same as that used for a similar comparison performed following Hurricane Andrew. The approach uses a probabilistic "Bayesian" updating process to determine the adequacy of the API RP 2A platform structure design process, based on "observed" platform failures and survivals during hurricane Lili. The result is a *bias factor* that reflects how well API RP 2A predicts platform behavior under extreme loads.

2.0 Platform Performance in Hurricane Lili

2.1 General Storm Characteristics

Hurricane Lili began its track on September 21, 2002 as a tropical depression over the Atlantic Ocean. Lili moved across the Windward Islands as a developing tropical storm on the 23rd, dumping heavy rains. The tropical storm weakened to a tropical wave on the 25th and 26th as it crossed the central Caribbean Sea. Lili regained tropical storm status on the 27th moving slowly around the north coast of Jamaica. Strengthening in the warm waters of the Caribbean, Lili hit western Cuba on October 1st as a Category 2 hurricane on the Saffir-Simpson scale. It moved into the Gulf of Mexico with winds of 145 mph as a Category 4 hurricane on the 2nd. Lili made landfall on the Louisiana coast on the 3rd as a borderline Category 1/Category 2 hurricane.

The hurricane path included a region of the Gulf that is densely populated with offshore platforms (Figure 2.1). The center of the hurricane traversed the Green Canyon, Ship Shoal, Eugene Island, South Marsh Island and Vermilion areas. Approximately 800 platforms were exposed to significant wind and waves from Lili [4]. Approximately 550 of these were exposed to the higher level Category 3 and 4 storm waves. As is typical in the Gulf of Mexico, the advance warning of hurricanes allowed some 25,000 workers to be evacuated from Gulf facilities prior to the storm reaching the area [4].

In some areas, Lili's waves were nearly as large as those used for the design of new structures. The regions of platforms most significantly loaded by Lili, as defined by the Minerals Management Service (MMS), included the Eugene Island and Ship Shoal areas. Some of the platforms in these regions were older structures that were not originally designed to withstand the forces created by a hurricane of Lili's magnitude.

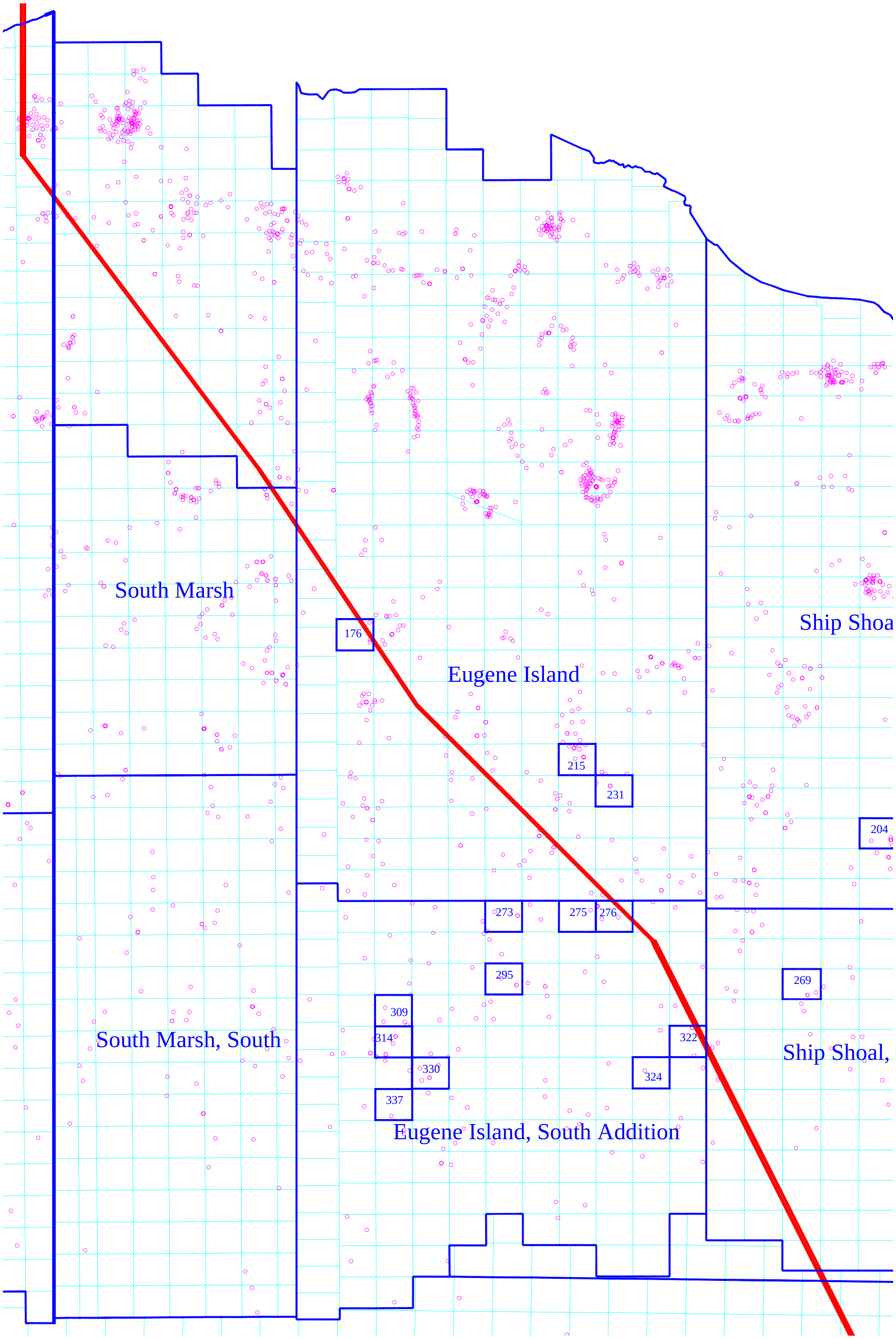

Figure 2.1 Storm track of Hurricane Lili through GOM OCS (platforms shown as pink circles, blocks with damaged platforms outlined and labeled)

2.2 Platform Performance in Lili

Overall, the Gulf of Mexico platform fleet performed remarkably well – with most platforms surviving the storm with no major structural damage and able to return to operation as soon as staff returned to the facility.

Table 2.1 shows the 17 platforms that were identified by the MMS as sustaining significant damage from Lili. This information was gathered from reports sent to the MMS by platform owners.

Several platforms sustained structural damage to horizontal and vertical members. A number of platforms were severely damaged ranging from failing deck members, failed jacket/pile connections, failed legs, buckled members, cracked joints and even mud-mat shifting. Hurricane Lili also resulted in the complete collapse of two platforms during the storm (EI 275 and EI 309). Some other key findings are:

- **Age.** As with prior hurricanes, age is the biggest factor in platform performance. Fourteen of the significantly damaged platforms were installed prior to 1980. Platforms in this era were designed when API RP 2A was still evolving and often had lower decks, smaller members and weaker joints than post-1980 platforms. These findings are consistent with those from Hurricane Andrew.
- **Wave-in Deck.** Several of the pre-1980 platforms were known to have low decks and likely failed due to the large forces exerted on a platform should a wave crest hit the deck structure.

For ten of the significantly damaged platforms, the damage was noticeable immediately following Lili. The MMS had required subsea inspections for platforms along the path of highest waves following Hurricane Andrew in 1992. The MMS also required this type of inspection following Lili, via a Notice to Lessees (NTL) No.: 2003-G04 issued in January of 2003. Such a Special Survey following an extreme event is also recommended in API RP 2A, Section 14.4.3 [5]. The NTL required differing API Level surveys as follows:

- **Level I – above water visual** - all platforms exposed to wind speeds greater than 74 mph.
- **Level II – general underwater visual by divers or ROV** - all platforms located within 25 miles of Hurricane Lili's eye center storm track while it was a category III/IV.
- **Level III – underwater visual inspection of areas of known or suspected damage** - all platforms that experienced wave loading in the deck and where Level II survey results prescribe Level III surveys.

The MMS also encouraged operators to first inspect the older platforms located nearest to the eye center storm track, and then gradually inspect those platforms towards the outer limits of the

MMS defined area. The inspections were to begin immediately. All work to correct any damage found during the inspection was to be completed by June 1, 2003 – the beginning of the next hurricane season.

Following these underwater inspections, eight additional platforms were identified with significant structural damage that had not been apparent immediately following the storm. These platforms are shaded gray in Table 2.1. These findings validate the rational in API RP 2A and the MMS NTL of underwater inspections following extreme events.

Table 2.1. Platforms with Significant Damage

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EI	324	Installed in 1990 in 260 feet of water. MMS indicated that the platform damage was severe enough to require removal.
EI	330a	Installed in 1971 in 244 feet of water. Post-Lili underwater survey identified heavy damage.
EI	330b	Installed in 1971 in 248 feet of water. Post-Lili underwater survey identified heavy damage.
EI	337	Installed in 1982 in 268 feet of water. Post-Lili underwater survey identified heavy damage.
SS	204	Installed in 1968 in 100 feet of water. Post-Lili underwater survey identified crack indications in conductor guide framing members at the (-) 25' elevation.

Area	Block	Description of Platform and Damage
SS	269	Installed in 1965 in 170 feet of water. Post-Lili survey identified 8 broken or missing vertical diagonal members through the splash zone.

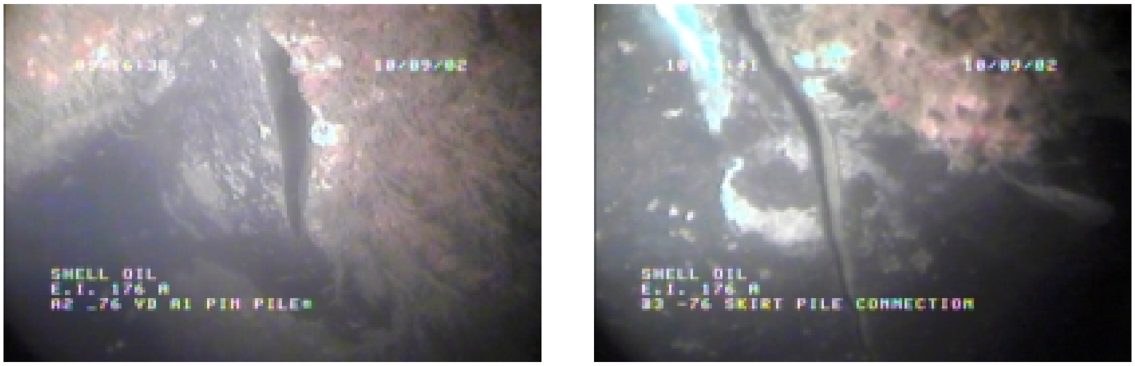
2.3 Damaged Platform Case Studies

The following describes some of the "global" damage to several of the platforms identified in Table 2.1.

Eugene Island 176 "A-VALVE" Platform (Shell Offshore)

This platform was installed in 1958 in approximately 80 feet of water. It was a skirt pile structure. At the time of the storm event, its original decking had been removed and its wells permanently abandoned. Three of its twelve slots were drilled. The jacket, heliport and conductors were still present during the hurricane.

Subsea inspections identified major cracks and tears in the vertical diagonal connections from the main jacket legs to the skirt piles (see the photos below). The platform was non-producing and it was felt that removal was the best option. This was planned for the summer of 2003.



Damage to EI-276-A-VALVE identified during subsea inspections at connections between the skirt piles and the main jacket

Eugene Island 215 "D01" Platform (McMoRan Oil & Gas)

This platform was installed in 1983 in approximately 100 feet of water. It supports two conductors, one producing and one shut in at the time of the storm.

Though subsea inspections after the storm did not find evidence of damage, the platform had a visible lean after the hurricane. McMoRan decided to abandon this platform.

Eugene Island 231 "CA" Platform (ChevronTexaco)

This four-leg platform was installed in 1968 in approximately 110 feet of water. This uniquely configured structure used conductors as two of its legs and conventional piled legs for the other two. There were four conductors in total, one of which was permanently abandoned prior to Hurricane Lili and the other three shut in. The facility was not manned and had no processing equipment.

Damage to this facility was apparent without underwater survey. There was gross lateral global deflection of the structure, including bulging noted in one leg above the water line. Visual indications, separated members and missing members were also noted from the post-storm underwater survey. The facility was bridge connected to the adjacent "A-PROD" platform, however this bridge was destroyed during the storm and its failure caused some of the damage to the "CA" platform.

ChevronTexaco elected not to repair this facility and it was removed in October 2003.

EI-231-CA is on the left. This is a post-storm photo and the bridge that used to connect the two facilities was destroyed in the storm.

Note the gross permanent deflection of the structure in this post storm photograph of EI-231-CA

Eugene Island 273 "A" Platform (Forest Oil)

This eight leg platform was installed in 1970 in 191 feet of water. This is a self-contained drilling and production platform with permanent quarters for six people. Twelve of its eighteen slots are drilled and it has gas compression equipment. In April 2001 a well fire occurred during drilling operations causing damage to main deck steel from heat and the failure of the derrick. During planning of repairs for this damage, Hurricane Lili passed through the Gulf.

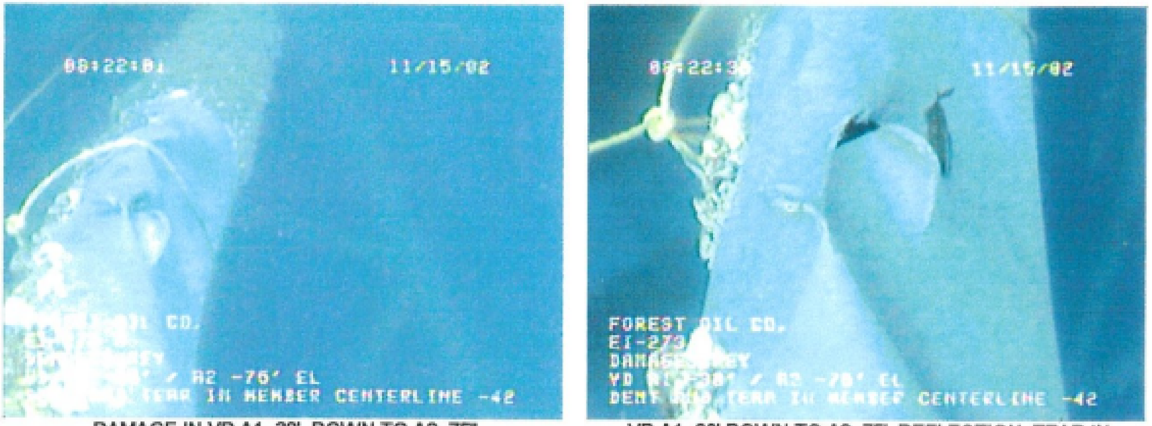
An underwater survey performed on October 10, 2002 (seven days after the hurricane made landfall) identified four damaged k-nodes in the transverse framing rows. Also impact damage to a vertical diagonal was identified. The damaged nodes are in the vertical framing for Rows 1 and 2 (the platform's conductors are primarily located between these two rows) at El. (-)75' and El. (-

)130'. At all four locations, the vertical framing members are the same size (both diameter and wall thickness) as the chord member. This type of configuration for k-nodes is relatively common in older platforms and known to be a weak point in the vertical load path.

The vertical member damage appears to be from an impact from a falling object. It consists of a dented portion of a vertical diagonal between A2 (-)75' and A1 (-)30' with a crack in the dent.

Analysis of the structure was performed using Sudden Hurricane loads per API RP 2A, Section 17 and additional underwater surveys were performed on highly stressed joints. No additional damage was found. Clamp repairs to the four damaged k-nodes were planned for this structure.

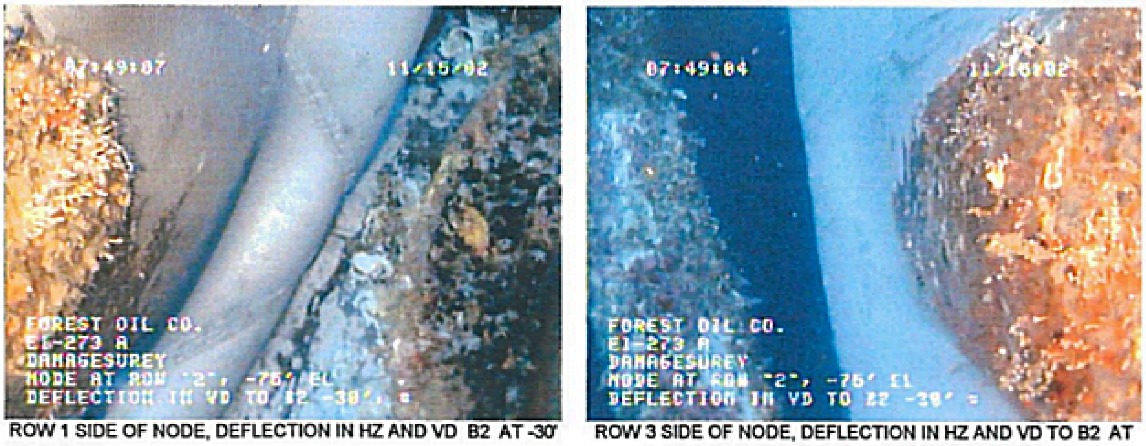
EI-273-A shown before the storm (left) and after the storm (right). The deck damage apparent in the post-storm photo is due to a well fire incident in 2001. Storm damage is evident in the survey images below.



DAMAGE IN VD A1 -30' DOWN TO A2 -75"

VD A1 -30' DOWN TO A2 -75', DEFLECTION, TEAR IN MEMBER FROM A2 LOOKING UP

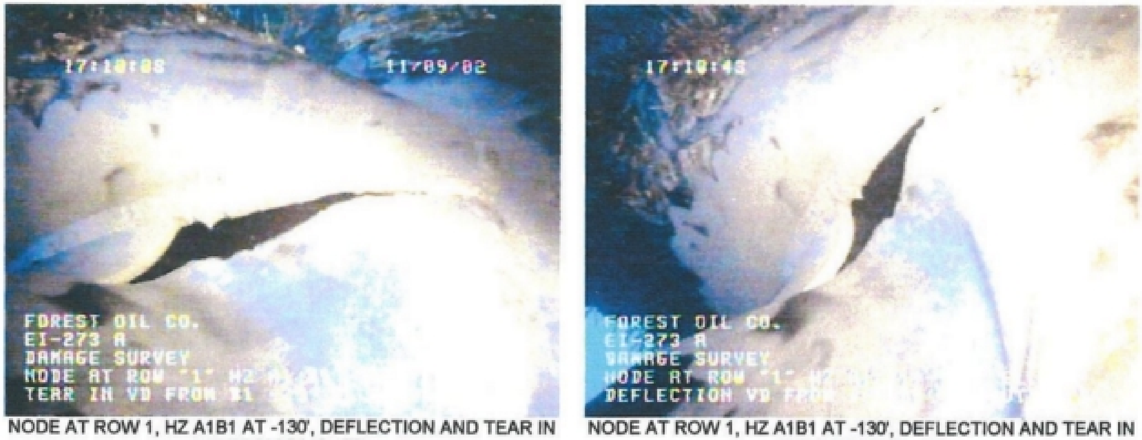
EI-273-A damage identified during post-storm subsea survey to vertical diagonal member between El. (-)30 and El. (-)75. Damage is believed to be from impact with falling object.



ROW 1 SIDE OF NODE, DEFLECTION IN HZ AND VD B2 AT -30'

ROW 3 SIDE OF NODE, DEFLECTION IN HZ AND VD TO B2 AT -30'

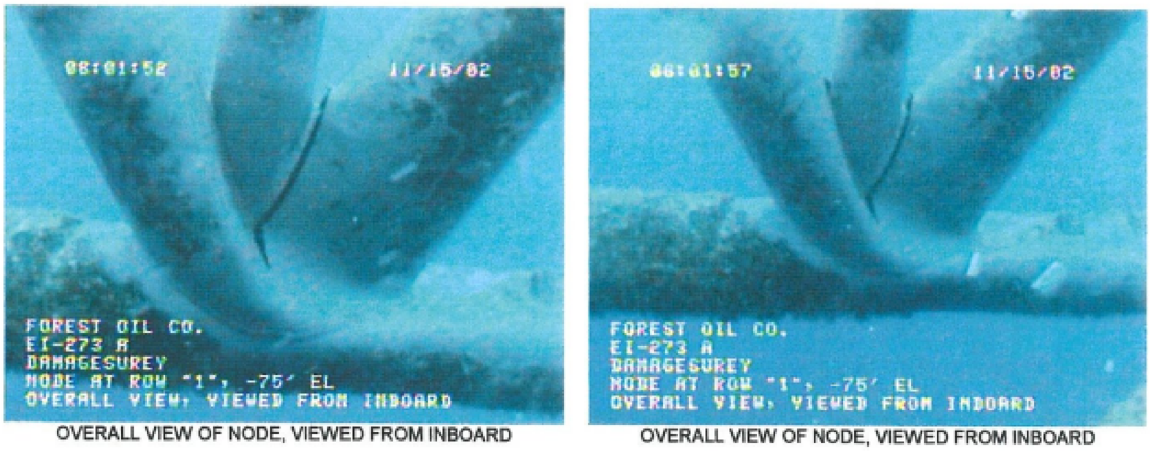
EI-273-A damage identified during post-storm subsea survey to k-node at El. (-)75. Note the gross deformation of the steel in the image on the left.



NODE AT ROW 1, HZ A1B1 AT -130', DEFLECTION AND TEAR IN VD FROM B1 @ -75'

NODE AT ROW 1, HZ A1B1 AT -130', DEFLECTION AND TEAR IN VD FROM B1 @ -75'

EI-273-A damage identified during post-storm subsea survey to k-node at El. (-)130.



OVERALL VIEW OF NODE, VIEWED FROM INBOARD

OVERALL VIEW OF NODE, VIEWED FROM INBOARD

EI-273-A damage identified during post-storm subsea survey to k-node at El. (-)75. Note the large crack between the vertical member and the vertical diagonal due to structural overload.

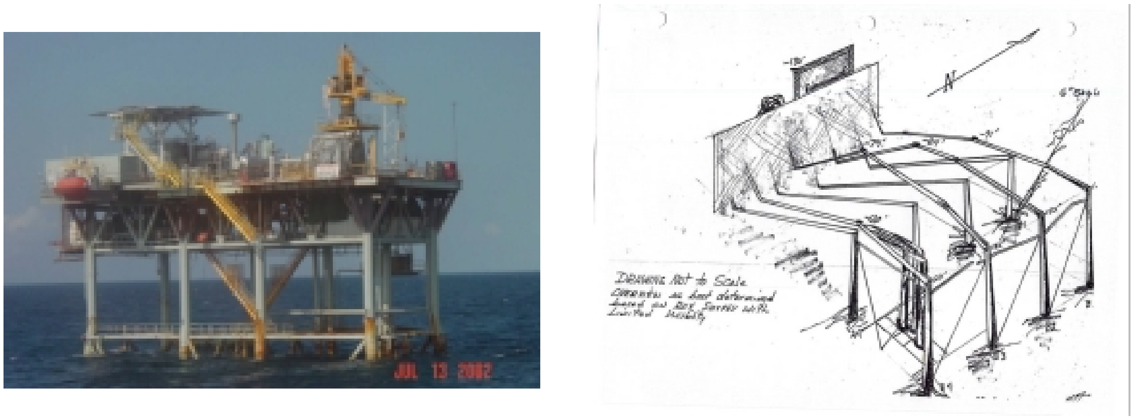
Eugene Island 275 "A" Platform (TotalFinaElf)

This eight leg platform was installed in 1964 in 172 feet of water. This jacket had typical vertical framing with single diagonal braces in the longitudinal rows and k-braces in the transverse rows. Four of twelve slots were drilled and the facility had gas compression equipment, a crane and other production equipment. Permanent quarters for twelve were installed on the platform.

EI-275-A was toppled by Lili. In 2000, the platform passed a Section 17 reassessment process using Sudden Hurricane criteria. This assessment was triggered by damage caused by a fire on the facility. Previous assessments in 1997 evaluated the impact of corrosion damage identified on the platform.

Even though the structure passed the design level checks performed in 2000, the operator and the MMS knew the platform would not withstand storm forces much greater than that expected during a Sudden Hurricane event. Plans were underway to abandon the remaining wells and remove the jacket structure to an approved reef site nearby when the storm hit.

Lili imposed forces on EI-275-A that were much greater than Sudden Hurricane forces and, as a result, the platform collapsed. Due to the assessment process the operator was able to sustain production for an additional 5 years, taking the risk of higher removal cost should the platform be destroyed prior to production ceasing and normal removal operations being completed.



EI-275-A shown before the storm (left) and after the storm (right) in a sketch based on ROV data. Additional observations indicate that the deck had separated from the jacket – a typical result when waves hit the deck.

Eugene Island 276 "B-AUX" Platform (Unocal)

This four-leg platform was installed in 1971 in approximately 172 feet of water. This is a fairly typical four-leg structure with single diagonal vertical framing in each row. This auxiliary platform is bridge connected to both a quarters platform and a production platform. It supports a helideck, sump, and various pieces of production equipment.

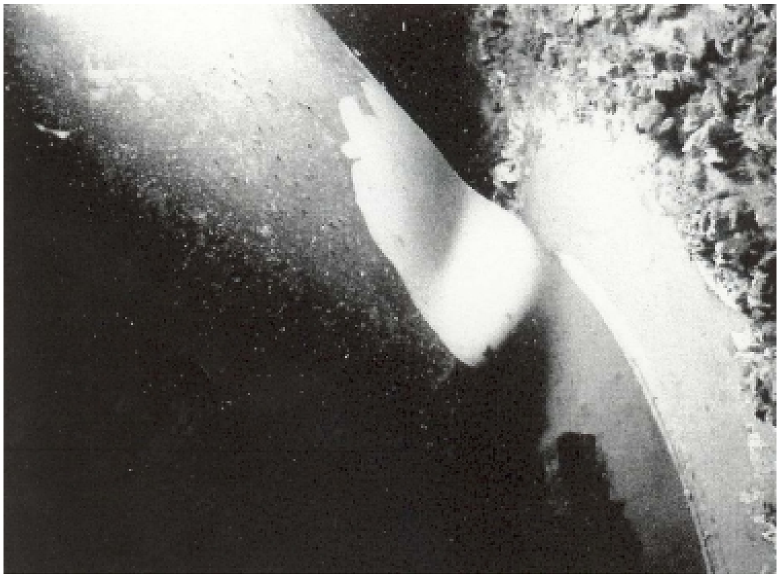
Damage to this facility was not apparent prior to the post-storm underwater survey. The survey discovered a damaged vertical diagonal running through the splash zone, damaged sump framing for a 36" diameter sump casing, and a severely damaged leg all on the south face of the platform near the first underwater level at El. (-)26.

Assessment of platform was performed using Sudden Hurricane criteria per API RP 2A, Section 17 consistent with an L-2 Exposure Category facility. Repairs were designed for the structure and included:

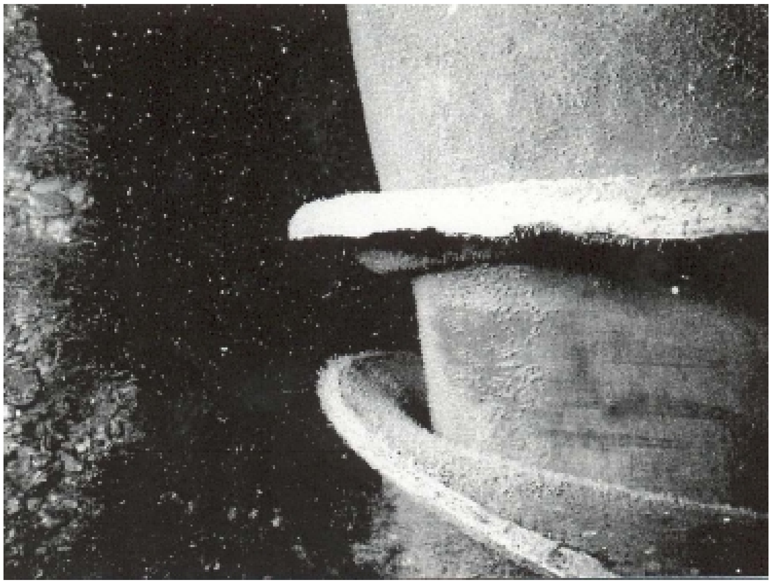
- Replacement of the damaged vertical diagonal using a doubler/slip-sleeve attachment at the leg below water and direct welding to the leg above water.
- Grouting of all jacket legs and the installation of a grouted clamp around the buckled portion of Leg B2 near El. (-)26'
- Removal of the sump casing and the framing elements at El. (-)26' and installation of two clamps over the holes on the remaining horizontal perimeter framing.

These repairs were completed in May 2003 and the platform is again operational. In order to limit exposure of personnel during the repairs to possible platform failure due to large waves, , the AUX facility was operated only during periods when a 12-hour weather forecast showed no seas greater than 12.5 feet.

EI-276-B-Aux shown in the rear left of this photo before Hurricane Lili



EI-276-B-Aux damage identified during subsea survey after the storm shows buckling to vertical diagonal brace.



EI-276-B-Aux damage identified during subsea survey after the storm shows deformation of Leg B2. This photo shows how the leg has been pounded "flat" form the cyclic motions of the platform. The pile can also be seen. The owner repaired this damage using a specially designed clamp.

Eugene Island 295 "A-PRD" Platform (Nexen Petroleum)

This four-leg platform was installed in 1972 in approximately 215 feet of water. This is a fairly typical four-leg structure with k-braced vertical framing in each row. This production platform contains no wells and is bridge connected to the eight-leg drilling platform, EI-295-A.

Damage to the drilling platform (EI-295-A) was relatively minor including boat landing, walkway, and stair damage (all below the cellar deck). No evidence of wave-in-deck loads was found. Damage to the production platform (EI-295-A-PRD) includes both jacket and deck damage and indicates that waves crested roughly five feet above the cellar deck level.

Deck damage includes cellar deck plate girders with permanent rotation and displacement including cracks at welds and secondary steel damage. Also, there was damage to the bridge support framing. Jacket damage includes a severed jacket leg (Leg A2) near the horizontal level at El. (-)33', failed k-node in Row A at El. (-)33', one of the VDs framing into that failed node is twisted and cracked, and the VD framing into A2 from below El. (-)33' near the failed leg shows signs of crack indications. No damage to the two risers on the platform was noted.

An assessment of the "A-PRD" platform was performed after Lili following the guidelines of API RP 2A, Section 17 using Sudden Hurricane criteria suitable for the L-2 Exposure Category. This assessment established a minimum RSR for the structure of just above 1.0 indicating acceptable performance in its damaged condition.

During assessment, production operations on the "A-PRD" platform were halted and temporary production was established on the "A" platform. After reviewing repair alternatives, the decision was made to permanently abandon operations on the "A-PRD" platform and establish permanent production facilities on the "A" platform including relocation of two risers from "A-PRD" to "A". The platform and bridge were removed in the summer of 2003.

EI-295-A-PRD is shown in a pre-storm photo on the left. The drilling platform is on the right.

EI-295-A-PRD deck damage is shown here after the storm. Note the deflected beams on the underside of the deck.

EI-295-A-PRD bridge damage is shown here after the storm. Note the cracked brace in the center of the photo. The bridge deflected several inches during the storm.

Eugene Island 309 "C" Platform (Forest Oil)

This four-leg platform was installed in 1969 in 218 feet of water. The platform had eight conductors, gas compression equipment, a helideck and other production equipment. The platform was unmanned.

This structure was toppled by Lili.

EI-309-C is shown in this pre-storm photo.

Eugene Island 314 "A" Platform (ExxonMobil)

This platform was installed in 1973 in approximately 235 feet of water. It supports 18 conductors. It is bridge connected to the production platform "A-PRD".

This platform lost a boat landing during the storm which necessitated a subsea inspection to determine if additional damage had occurred. The survey discovered a vertical diagonal, from B1 at El. (-)200' to A1 at El. (-)160', imploded along about 95' of its length, various dents of up to 6" size and one member abraded to bare metal. Only that portion of the platform within the area of the fallen boat landing was inspected. The boat landing was discovered intact at the bottom of the platform.

An assessment of the structure was performed according to the guidelines of Section 17, using Sudden Hurricane criteria and including the damage found.

Eugene Island 322 "A" Platform (BP America)

This four-leg drilling platform was installed in 1978 in approximately 235 feet of water. It is bridge connected to the production platform "A-PRD". 13 of 15 slots are drilled. The vertical framing consists of x-bracing in each face.

Damage was apparent to the structure even before underwater inspections were performed. Significant, global structural deformation and displacement could be seen after the storm. Subsequent detailed analyses indicated that the failure of a jacket/pile weld on one of the leeward legs in addition to a severed pile below the mudline led to much of the damage sustained by the platform.

BP determined that they needed to abandon this platform and have work to develop a safe process in which to stabilize the system while the wells could be plugged and abandoned, the topsides equipment removed and the platform ultimately toppled in place. BP also elected to topple the drilling platform. Both platforms were successfully toppled in May 2004. See also OTC 2004 paper Number 16801.

EI-322-A shown both before the storm (left) and after the storm (right).

Eugene Island 324 "A" Platform (Newfield)

This four-leg production platform was installed in 1990 in approximately 260 feet of water. Seven of eight slots have been drilled and the platform supports a helideck, gas compression equipment, a crane and other production equipment.

The damage this platform sustained during Lili was considered significant enough to warrant removal of the structure and this was accomplished during the summer of 2003.

EI-324-A shown in a pre-storm photograph.

Eugene Island 330 "A" Platform (Devon)

This production platform was installed in 1971 in approximately 240 feet of water. It supports 23 conductors, a quarters facility, gas compression equipment, two cranes, and other production equipment.

Three flooded members were identified during the post Lili underwater surveys, two at the (-)29' elevation and one at the (-)73' elevation. Several visual indications and MPI indications were identified at both these levels.

EI-330-A shown in a pre-storm photograph.

Eugene Island 330 "B" Platform (Devon)

This eight-leg production platform was installed in 1971 in 248 feet of water. It supports 18 conductors, a quarters facility, helideck, gas compression equipment, two cranes, and other production equipment.

There has been subsidence at the platform site, approximately 10 feet since it was originally installed. Two separate Section 17 reassessments have been performed in the past to address this issue, once in 1997 and again in 1999 when Devon bought the facility. In 1999, the pushover assessment demonstrated sufficient capacity to withstand a Sudden Hurricane storm.

No evidence of wave-in-deck was identified during post-Lili inspections.

EI-330-B shown in a pre-storm photograph.

Eugene Island 337 "A" Platform (Devon)

This production platform was installed in 1982 in 268 feet of water. It supports 8 conductors, a quarters facility, gas compression equipment, two cranes, and other production equipment.

The damage noted during post-storm underwater surveys included a hole in a horizontal member caused by a secondary brace supporting a sump casing being pulled out.

EI-337-A shown in a pre-storm photograph.

Ship Shoal 204 "A" Platform (Anadarko)

This drilling platform was installed in 1968 in 100 feet of water. It supports 24 conductors and a quarters facility. It is bridge connected to a compressor platform and a production platform creating a three-platform unit.

Subsea damage was noted on the drilling platform at the (-)25' elevation conductor guide framing. Damage consisted of crack indications. Damage was also noted to the bridge connecting the drilling and compressor platforms. The bridge was shifted towards the compressor platform causing minor damage.

Ship Shoal 269 "A" Platform (Maritech Resources)

This eight-leg platform was installed in 1965 in approximately 200 feet of water. This is a fairly typical eight-leg structure with single diagonal and k-brace vertical framing. The facility is bridge connected to the "A-AUX" platform and has 13 drilled slots.

Damage to this facility was not apparent prior to the post-storm underwater survey. The survey discovered several separated and missing members, primarily vertical diagonals between El. (+)10' and El. (-)30'. Assessments were performed to determine the appropriate course of action and develop plans to repair the damage and continue to use the platform.

SS-269-A shown in a pre-storm photograph

2.4 Component Performance

In addition to the global performance of the platforms as demonstrated by the Case Histories, specific component damage was also of interest. Some examples are:

- **Braces.** Damage ranged from local buckling to global buckling to completely severed members.
- **Joints.** Damage at typical tubular joints included small to large cracks in welds, joint deformation, and complete brace pull-out from the chord. Large cracks were also located in several skirt pile connections on one platform.
- **Appurtenances.** Damage was reported to many jacket appurtenances such as boat landings, barge bumpers, walkways, handrails and stairs. In one case the boat landing came off the platform and fell onto several brace members below, further damaging the structure. However, in most cases this type of damage was not a significant structural concern.
- **Deck Structure.** The most serious damage was the bending of deck beams due to the large forces at the top of wave crests. Other damage included many instances of displaced deck grating.
- **Deck Equipment.** Waves and high winds caused damage to process and control equipment as well as items not crucial to structural performance. This type of damage can be costly to repair and can cause delays in restarting the facility following a hurricane.

2.5 Hurricane Lili – Additional Lessons Learned

The following section describes lessons that we have learned or re-learned from the impact of Lili on fixed steel offshore platforms in the Gulf of Mexico. This information was gathered from post-storm investigations relating to how operators make decisions and the impact of those decisions.

2.5.1 Concentration of an Operator's Platforms in a Single Location

The tendency for operators to have a large number of platforms grouped together in a relatively small geographical area is useful for a number of operational considerations: personnel transfers, stores replenishment, maintenance operations, etc. However, since many hurricanes tend to directly impact a relatively narrow band of OCS blocks (e.g., South Timbalier in Hurricane Andrew and Eugene Island in Lili) an operators entire fleet (or a significant portion of it) can all be put at risk from a single event.

As an example, one operator had over 70 platforms experience damage (mostly minor) in Lili. Although the damage to each platform was minor, the cumulative effect was significant. In addition, this represents a large portion of their total fleet and all were grouped together in fairly close proximity. This single event impacted their ability to recover from the storm since so many of their properties had to be assessed and in some cases repaired.

From this experience, the operator made a decision to diversify their platform fleet so that they have a broader geographic spread with less likelihood of a single storm event directly affecting a large percentage of their fleet. This does not eliminate the risk of platform damage or failure on an individual basis, but it does help prevent widespread downtime for an operator's fleet after a major event.

2.5.2 The Usefulness of API RP 2A Section 17 Demonstrated

Section 17 of API RP 2A provides operators with a methodology for reassessing older platforms in their fleets when changes to its operation are considered or damage and other anomalies are found. The response of operators to the findings of these reassessments can directly impact the success or failure of a facility to withstand a major storm event such as Lili.

The experiences of ChevronTexaco and TotalFinaElf previously noted for platform's EI-252-C/L and EI-275-A respectively, provide good examples of two different responses to reassessment results. In ChevronTexaco's case, the operations group was interested in adding production capacity to one of their facilities, but the engineering group determined, using the Section 17 process, that the facility would not be able to support the added facilities and withstand a major storm. Thus the investment in the new production capacity would be at what ChevronTexaco considered to be an unacceptable risk. They decided to expand capacity and strengthen the existing facility through the addition of a new platform adjacent to and connected to the existing one. This combined facility was in the path of Lili and withstood its impact with no significant damage. Thus the investment in increased capacity at that location was protected.

TotalFinaElf took a different approach to their platform reassessment results. Similar to ChevronTexaco, their results indicated that their facility would not be able to withstand a significant storm event. However, the economics of that particular field did not justify the cost of strengthening the platform. Instead, a gradual reduction in operations was planned for that facility and its decommissioning was started. When Lili hit, the platform was largely non-operational which was fortunate because the wave-in-deck loads from the storm waves toppled the platform. However, the knowledge gained from the reassessment process, allowed the operator to plan for the removal of that facility and its ultimate failure during the storm did not impact their overall operations, or the environment, which would not have been the case if it had been operating in a normal manner.

The reassessment process provides operators a means of evaluating their older facilities and make proactive decisions on how to continue operations.

2.5.3 The Cost of Platform Damage and Cleanup can be Significant

Despite the best efforts of operators to maintain their facilities and keep them operating normally, failures of platforms do occur. Sometimes these failures are caused by fabrication flaws or unknown damage that weakens the normal load path of the structure. Whatever the reason, the cost of these failures can be considerable.

In order to maintain a safe work environment and provide protection for the environment, novel and, sometimes, expensive methods are required to safely decommission a platform that has been damaged in a storm. Primary considerations for these decommissioning operations are removing production facilities from the topsides, permanently plugging and abandoning the operating wells, and disposing of the jacket structure through removal or reefing operations. These operations can be expensive under the best conditions, but when a facility has been weakened through storm damage, the costs can rise dramatically.

BP was faced with this problem when a fabrication flaw and an unknown pile failure led to failure of the platform. Thirteen wells had to be plugged and abandoned from the deck of an unstable structure. The decision was made to strengthen the structure to allow the well decommissioning and removal of the topsides equipment and structures, and then to topple the facility (and the adjacent, otherwise undamaged platform) once those operations had been completed. Extensive work was required to analyze the structure, design and fabricate the repairs, install the strengthening system, plug and abandon the wells, decommission the facility and then topple the remaining structure.

While this is an atypical event, it does demonstrate that the removal of damaged platforms can be expensive. The ability to evaluate and execute novel approaches to solving these problems offshore is important and depends on experienced staff working in concert with industry consultants and contractors. Operators should consider the potential cost of platform failures in their economic decision processes.

3.0 Comparison of Platform Performance to API RP 2A

3.1 Reliability Procedure and Comparison to Hurricane Andrew JIP Results

The second part of the study involved a comparison of the expected performance of platforms in Lili based upon API RP 2A analytical approaches, to the actual observed performance (platform survived, was damaged or failed). The approach used a probabilistic "Bayesian" process that was the same as that used for a similar comparison performed following Andrew.

This section discusses this work. The reliability methodology used in the procedure is first explained, including the selection the values for the variables in the associated probabilistic distributions. The method used in this study for Lili was then tested using the Andrew data to ensure that the same results are achieved as for the previous Andrew work. The specific Lili results are then described along with the results of combining the Lili and Andrew results. Based upon these results, conclusions are made on the adequacy of API RP 2A for platform design.

Appendix A provides additional back-up data for this work.

3.1.1 Reliability Methodology

The bias factor, B, is defined as the ratio of the true safety factor to the computed safety factor. In term, the safety factor is defined as the ratio of structural resistance (R) to load (S). This can be written as

$$\left[\frac{R}{S}\right]_{true} = B \cdot \left[\frac{R}{S}\right]_{computed} \tag{3.1}$$

Determination of the bias factor gives an indication of the accuracy of the computed (according to API RP2A Section 17 procedure) platform safety factor. A value of $B<1$ indicates that the computed platform safety factor is un-conservative, and a $B>1$ indicates that the computed platform safety factor is conservative.

A methodology was introduced in previous Andrew studies [1, 2] to determine the bias factors for several chosen platforms that were either damaged or survived during Hurricane Andrew. This study follows a similar methodology.

Formulations

The first step in determining the bias factor is to compute the probability of platform failure. The conventional formula for computing the probability of failure is:

$$P_f = \int_0^{\infty} \left(1 - F_s(x)\right) f_R(x) dx \qquad (3.2)$$

where F_s is the cumulative distribution function for the load variable S, and f_R is the probability density function for the resistance variable R.

The load variable S is represented by the base shear (*BS*) on the platform, which in term can be expressed by the following equations:

$$BS = C_1 \left[h + C_2 u\right]^{C_3} \varepsilon_o \qquad h <= h_d \qquad (3.3)$$

$$BS = \left[C_1 + C_4 (h - h_d)\right]\left[h + C_2 u\right]^{C_3} \varepsilon_o \qquad h > h_d \qquad (3.4)$$

where h is the wave height (ft),
u is the current speed (knot),
h_d is the height of platform cellar deck (ft),
C's are coefficients to be determined, and
ε_0 is a model uncertainty factor representing the accuracy in base shear equation.

The distribution of the wave height, h, is given by the Forristall distribution with the following form:

$$f_{H|H_s}(h|H_s = h_s) = \frac{\alpha 4^{\alpha}}{\beta H_s} \left(\frac{h}{H_s}\right)^{\alpha - 1} \exp\left[-\frac{4^{\alpha}}{\beta}\left(\frac{h}{H_s}\right)^{\alpha}\right] \qquad (3.5)$$

in which α = 2.126 and β = 8.42, and h_s is the significant wave height at a particular hour at the considered platform location from hindcast data.

The maximum base shear for a multi-hour, multi-directional storm can be written as

$$F_{MBS} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \prod_{hour\_j}^{Hours} \left\{ \int F_{BS}\left(x \middle| H = h_s, U = u_j\right) f_{h|H_s}\left(h \middle| H_{sj} = h_{sj}\right) dh \right\}^{Nj} f_{\varepsilon 1}(\varepsilon_1) f_{\varepsilon 2}(\varepsilon_2) d\varepsilon_1 d\varepsilon_2 \quad (3.6)$$

F_{BS} is a log-normal cumulative distribution combined from equations (3.3), (3.4) and (3.5), N_j is the number of waves in a storm hour, and ε_1 and ε_2 are model uncertainties in the hindcast significant wave height and current data.

Similar to equation (3.2), the probability of failure for a given bias factor *b*, is

$$P_f(b) = \int_0^\infty (1 - F_s(bx)) f_R(x) dx \qquad (3.7)$$

Direct numerical integration on the above equation is not the most efficient way to compute $P_f(b)$. Rather, in the Andrew Phase 2 JIP study [2], a nested inner and outer loop FORM (First Order Reliability Method) method was used to determine this probability of failure.

Random variables are categorized by their appearance in either the inner or outer loop:

Inner loop random variables, *Y*

- Individual wave height, $H|H_s$.
- Model uncertainty factor in base shear calculation, ε_0 .

Outer loop random variables *X*

- Capacity, *R*.
- Significant wave height, H_s.
- Current velocity, *u*.

The inner loop consists of the probability of failure based on a single wave. The limit state function for this inner loop is

$$g(Y, X; b) = bR - BS \cdot \varepsilon_0 \qquad (3.8)$$

The limit state function for the outer loop can be written as

$$g(U, X; b) = U - \Phi^{-1}\left[1 - (1 - P_f(x, b))^n\right] \qquad (3.9)$$

Where *U* is an auxiliary variable (standard normal distribution with mean of 0 and standard deviation of 1), *n* is the number of waves in a storm hour. It can be theoretically shown that solutions from the nest reliability problem, Eqs.(3.8) and (3.9), are equivalent to the original failure probability definition, Eq.(3.7).

3.1.2 Random Variables and Bayesian Updating Definition

The random variables used in the analysis are listed in Table 3.1, which are taken to be the same from Andrew Phase 2 JIP study [2].

Table 3.1 – List of Random Variables

Variable	Distribution	Expected Value	COV
Capacity , R	Log-Normal	per analysis	0.15 for jacket capacity 0.20 for foundation lateral capacity 0.30 for foundation axial capacity
Individual wave height, h	Forristall	per hindcast	per formula
Hindcast error in Hs, ε_1	Log-Normal	1	0.1
Hindcast error in current, ε_2	Log-Normal	1	0.15
Wave to wave error in base shear, ε_0	Log-Normal	1	0.2 for wave below deck 0.25 for wave in deck

The bias factor *b* is further distinguished into a set of three bias factors (b_j, b_{fl} and b_{fa}), which represents the factors for jacket, foundation lateral capacity and foundation axial capacity, respectively. The reliability calculation calculates the failure probability for a specific set of bias factors (b_j, b_{fl} and b_{fa}). These reliability results are used to define the *likelihood function*, and then these likelihood functions are finally used in a Bayesian updating framework to estimate the probability distributions of b_j, b_{fl} and b_{fa}.

Depending on the degree of damage (damage/failure cases) or no damage (survival cases), the likelihood functions are defined differently. These are explained as follows, which are the same as used in the Andrew Phase 2 JIP study [2].

The platforms were grouped into five categories:

1. Survival – No damage, or only minor non-structural damage identified.
2. Damage, Type I – Known damage to the jacket, foundation is assumed intact.
3. Damage, Type II – Known damage, but not attributed specifically to jacket or foundation.
4. Failure, Type I – Known failure of the jacket, foundation assumed intact.
5. Failure Type II – Known failure, but not attributed specifically to jacket or foundation.

Specific definitions of likelihood functions for these five categories are described as follows:

Category 1 - Survival Cases

The likelihood function for the survival case is

$lb(b_j, b_{fl}, b_{fa} | survival) =$

P(base shear < jacket damage capacity AND *base shear < jacket foundation capacity)* (3.10)

The platforms analyzed in this category were, ST151K and ST130Q (Andrew platforms).

Category 2 - Damage, Type I

$lb(b_j, b_{fl}, b_{fa} | damage1) =$

P(base shear is between jacket damage and collapse capacities AND *base shear < jacket foundation capacity)* (3.11)

The platform analyzed in this category was ST177B (Andrew platform).

Category 3 - Damage Type II

$lb(b_j, b_{fl}, b_{fa} | damage2) =$

P(base shear > jacket damage capacity AND *base shear > jacket foundation capacity)* (3.12)

The platform analyzed in this category was SS139 (Andrew platform).

Category 4 - Failure, Type I

$lb(b_j, b_{fl}, b_{fa} | failure1) =$

P(base shear > jacket collapse capacity AND *foundation capacity > jacket collapse capacity)* (3.13)

The platforms analyzed in this category were ST151H and ST130A (Andrew platforms).

Category 5 - Failure Type II

$lb(b_j, b_{fl}, b_{fa} | failure2) =$

P(base shear > jacket collapse capacity AND *base shear > jacket foundation capacity* (3.14)

The platform analyzed in this category was ST72 (Andrew platform).

Once an individual likelihood function is calculated (from nested FORM procedure as described earlier), a combined likelihood function is expressed as the multiplication of the individual functions.

$$lk(b_j, b_{fl}, b_{fa} | n\_observations) = \prod_{platform=1}^{n} \left[lk(b_j, b_{fl}, b_{fa} | observation) \right] \tag{3.15}$$

Bayesian updating provided the posterior distribution of the bias factors (f''_{B_j} , $f''_{B_{fl}}$ and $f''_{B_{fa}}$). The prior distributions of the bias factors (f'_{B_j} , $f'_{B_{fl}}$ and $f'_{B_{fa}}$) are assumed as normal distributions with a mean value of 1.0 for b_j and b_{fl}, 1.3 for b_{fa}, and a COV of 0.3 is assumed for all three bias factors.

The joint prior distribution is the product of the individual independent prior distributions.

$$f'_{B_j, B_{fl}, B_{fa}} = f'_{B_j} * f'_{B_{fl}} * f'_{B_{fa}} \tag{3.16}$$

The posterior distribution is the multiplication of the prior and the likelihood functions.

$$f''_{B_j, B_{fl}, B_{fa}}(b_j, b_{fl}, b_{fa}) = f'_{B_j, B_{fl}, B_{fa}}(b_j, b_{fl}, b_{fa}) * lk(b_j, b_{fl}, b_{fa} | n\_observations) \tag{3.17}$$

The marginal (e.g. individual) distributions for each of the bias factors can be obtained by integrating out the other two bias factors. Once the marginal distributions are obtained for each of the bias factors, their mean and coefficient of variation (COV) can be estimated.

3.1.3 Comparison of Current Calibration Results to Published Andrew Results

The methodologies used to compute the bias factors for the Andrew platforms in this calibration study are essentially the same as [2], however there are still some differences between the two need to be mentioned:

- C_1, C_2, C_3, C_4 values, see Eqs. (3.3) and (3.4) as shown previously, for the Andrew Phase II analysis [2] were not available, so the data was approximated from Phase I data ([1], in which some C factors are available), or from independent sources. The C factors used in this calibration study are not necessarily the same as the ones used in [2].

- Although both methods utilize nested inner and outer loops and FORM and SORM analysis, the programs used to calculate the probabilities were different which can contribute to some differences in the comparisons to be presented later. Also, numerical integrations used in the post-processing phase, and the estimation of mean and COV from a raw curve can result in differences when different algorithms are used.

Having mentioned the above calculation differences, a comparison of the bias factors from the Andrew Phase II study [2] and the current study are presented in Table 3.2. It can be seen from this table that the calculated bias factors are consistent with Andrew JIP Phase 2 results. This indicates the reliability methodology and programs established in this work are adequate.

The platform capacities, hindcast metocean data and other useful information for the calibrated Hurricane Andrew platforms are listed in Table 3.3.

Table 3.2 - Comparison of Andrew Phase II [2] and Current Calibration Results

			Phase II		**Current**	
			Mean	COV	Mean	COV
St151K	Survival	Bj	1.33	0.16	1.30	0.19
		Bfl	1.15	0.21	1.13	0.26
		Bfa	1.4	0.2	1.35	0.20
ST130Q	Survival	Bj	1.13	0.22	1.11	0.19
		Bfl	1.11	0.23	1.12	0.25
		Bfa	1.36	0.21	1.35	0.20
ST151H	Failure I	Bj	0.92	0.23	0.90	0.21
		Bfl	1.11	0.23	1.05	0.23
		Bfa	1.39	0.2	1.36	0.20
ST130A	Failure I	Bj	0.86	0.22	0.84	0.24
		Bfl	1.18	0.21	1.16	0.22
		Bfa	1.37	0.21	1.36	0.20
ST177B	Damage I	Bj	1.03	0.2	1.13	0.20
		Bfl	1.14	0.21	1.09	0.20
		Bfa	1.4	0.21	1.37	0.20
SS139	Damage II	Bj	0.95	0.23	0.88	0.26
		Bfl	1.09	0.23	1.05	0.26
		Bfa	1.36	0.21	1.35	0.20
ST72	Failure II	Bj	0.97	0.23	0.87	0.26
		Bfl	1.05	0.25	1.06	0.26
		Bfa	1.35	0.21	1.35	0.20
Combined	Survival	Bj	1.35	0.16	1.30	0.18
		Bfl	1.19	0.19	1.19	0.22
		Bfa	1.41	0.2	1.37	0.21
Combined	Damage	Bj	1	0.17	1.03	0.2
		Bfl	1.13	0.21	1.13	0.21
		Bfa	1.46	0.17	1.40	0.21
Combined	Failure	Bj	0.8	0.19	0.80	0.23
		Bfl	1.17	0.21	1.16	0.21
		Bfa	1.38	0.21	1.38	0.21
Combined	all	Bj	1.1	0.13	1.02	0.14
		Bfl	1.32	0.17	1.30	0.17
		Bfa	1.54	0.15	1.41	0.18

Table 3.3 – Platform Information Summary for Hurricane Lili Bias Factor Calculation (analyzed platforms highlighted in yellow)

Phase II

									Hindcast Hour 1			Hindcast Hour 2			Hindcast Hour 3							
Platform	**Category**	**Jacket Resistance Damage (kip)**	**Jacket Resistance Ultimate (kip)**	**Foundation Lateral Resistance (kip)**	**Foundation Axial Resistance (kip)**	**Max. Expected Base Shear (kip)**	**h_{max} (ft)**	**Height of Deck (ft)**	**Hs (ft)**	**Current (knots)**	**Tp (sec)**	**Hs (ft)**	**Current (knots)**	**Tp (sec)**	**Hs (ft)**	**Current (knots)**	**Tp (sec)**	**C1**	**C2**	**C3**	**C4**	**Logic**
ST151K	Survival	2900	3800	4230	4000	3757	59.1	52.5	34.7	2.0	13.1	34.6	2.0	13.0	31.8	1.8	12.8	0.233	6.521	2.258	0.001	$S<2900*b_j$ AND $S<4230*b_{fl}$ AND $S<4000*b_{fa}$
ST130Q	Survival	1380	1410	1470	1860	1032	58.3	60.0	33.3	1.9	13.0	33.7	1.8	12.9	32.0	1.6	12.1	0.035	6.770	2.414	0.001	$S<1380*b_j$ AND $S<1470*b_{fl}$ AND $S<1860*b_{fa}$
WD103A	Survival	4380	4700	4880	5040	2140	50.2		28.0	1.0	12.6	28.9	1.0	11.8	27.9	0.9	11.5					$S<4380*b_j$ AND $S<4880*b_{fl}$ AND $S<5040*b_{fa}$
ST151H	Failure I	2680	3140	3970	3580	3551	59.1	55.0	34.7	2.0	13.1	34.6	2.0	13.0	31.8	1.8	12.8	0.522	7.284	2.031	0.013	$S>3140*b_j$ AND $3140*bj<3970*b_{fl}$ AND $3140*bj<3580*b_{fa}$
ST130A	Failure I	2000	2930	1800	2860	2322	55.4	72.5	31.7	1.8	12.8	32.4	1.8	12.8	30.9	1.6	11.7	0.131	6.646	2.326	0.0001	$S>2930*b_j$ AND $2930*bj<1800*b_{fl}$ AND $2930*bj<2860*b_{fa}$
ST177B	Damage I	3900	5210	4700	3700	4496	59.6	42.5	35.9	2.5	13.3	32.2	2.4	13.0	31.1	2.3	12.7	0.364	7.136	2.166	0.0001	$3900*bj<S<5210*b_j$ AND $3900*bj<4700*b_{fl}$ AND $3900*bj<3700*b_{fa}$
ST151J	Damage I	4640	5100	6000	5785	4450	58.8		34.6	2.0	13.1	34.5	2.0	13.0	31.7	1.8	12.8					$4640*bj<S<5100*b_j$ AND $4640*bj<6000*b_{fl}$ AND $4640*bj<5785*b_{fa}$
SS139 (T25)	Damage II	1250	1640	2240	2665	1224	43.5	50.6	21.1	2.6	13.9	26.0	2.6	13.0	24.5	2.5	12.8	0.655	2.106	1.935	0.0001	$S>1250*b_j$ AND $S>2240*b_{fl}$ AND $S>2665*b_{fa}$
ST72 (T21)	Failure II	1260	1610	3250	2700	1349	46.9	54.6	27.9	2.4	13.1	27.5	2.3	12.8	24.8	2.1	11.7	1.117	2.569	1.788	0.0001	$S>1610*b_j$ AND $S>3250*b_{fl}$ AND $S>2700*b_{fa}$
SPelto 10	Damage	38	48			65	35.8		20.0	2.8	13.0	21.0	3.0	11.9	19.1	3.0	11.5					
SS135	Damage	119	148			132	32.9		17.8	2.3	7.3	19.7	2.8	7.6	14.7	7.7	3.2					
SS136	Damage	173	224			139																

Definition	Survival	No damage observed in jacket or foundation
	Failure I	Jacket failed, but foundation remains intact
	Failure II	Failure is known, but not specifically attributed to jacket or foundation
	Damage I	Known damage to jacket, and foundation remains intact
	Damage II	Damage is known, but not specifically attributed to jacket or foundation

S is the base shear of jacket (a probabilistic quantity), caused by hurrican Andrew

Phase I

						Hindcast Hour 1			Hindcast Hour 2			Hindcast Hour 3					
Platform	**Category**	**Resistance (kip)**	**Max. Expected Base Shear (kip)**	**h_{max} (ft)**	**Height of Deck (ft)**	**Hs (ft)**	**Current (knots)**	**Tp (sec)**	**Hs (ft)**	**Current (knots)**	**Tp (sec)**	**Hs (ft)**	**Current (knots)**	**Tp (sec)**	**C1**	**C2**	**C3**
ST151K	Survival	3500	4473	60.9	52.5	33.9	1.9	13.7	36.2	2.0	14.5	33.5	1.8	13.9	0.169	6.210	2.360
ST130Q	Survival	1265	1214	62.3	60.0	35.2	1.7	13.7	36.8	1.8	14.2	34.1	1.5	13.6	0.011	5.118	2.725
ST151H	Failure	3999	4206	60.9	55.0	33.9	1.9	13.7	36.2	2.0	14.5	33.5	1.8	13.9	0.216	6.306	2.275
ST130A	Failure	3000	2779	61.0	72.5	33.9	1.9	13.7	36.2	2.0	14.4	33.5	1.8	13.8	0.084	5.845	2.427
ST177B	Failure	4168	5150	60.2	42.5	33.0	1.4	13.1	36.0	1.7	13.8	34.7	1.5	13.7	0.002	1.969	3.499
SS139 (T25)	Damage	1342	1691	50.6	50.6	29.6	2.0	13.3	30.1	2.1	15.8	27.8	1.5	14.4	0.655	2.106	1.935
ST72 (T21)	Failure	1984	1615	49.7	54.6	29.1	2.0	13.2	29.8	2.0	15.7	27.7	1.6	14.5	1.117	2.569	1.788

3.2 Bias Factors from Lili and Combined Lili/Andrew

A total of three Lili platforms are used in the evaluation process. These platforms are listed in Table 3.4 including the Platform Performance (Survival, Damage I) and the Jacket/Foundation Bias Factors. The Mean is the central value of the resulting probability distribution. As noted previously a value greater than 1.0 indicates that the API RP 2A process is conservative. For example, for SS 269 the Jacket Bias Factor Mean is 1.08. In other words, for this specific platform, the API RP 2A design process overestimates the ratio of [R/S] by about 8 percent. The COV is the Coefficient of Variation of the distribution, with a higher value meaning more variation. The typical values of 0.2 to 0.3 represent a reasonable confidence in the results.

It is noted that all of the bias factors exceed unity, even for the results from damaged platforms. This is because in these damaged platforms, the predicted maximum load is close or exceeds the collapse load. However, only damaged members (not collapse) were observed for these platforms. The fact that all of the bias factors exceed unity indicates that the API RP 2A process is conservative. In other words, it has predicted more damage and failure than was actually observed. The results should be considered as evidence supporting the use of the API process developed by industry in that they appear to be conservative overall. It is not recommended that the calculated bias factors be applied to individual platforms in any assessment since they were derived from a small sample of platforms. Also, the individual platform bias factors ranged from 1.08 to 1.16 for jacket structure capacity, from 1.08 to 1.10 for foundation lateral capacity, and from 1.36 to 1.37 for foundation axial capacity indicating that the application of a single average bias factor on an individual platform may not be appropriate.

The Bias factors of the individual Lili platforms shown in Table 3.4, were combined to develop a single set of Bias factors as shown in Table 3.5. Also shown are the Hurricane Andrew Bias factors (nine platforms involved) from the Andrew JIP Phase II results, as well as the Lili and Andrew Bias factors combined. Figure 3.1 shows a graphical representation of the distributions. Results are generally similar for both Andrew and Lili – with an overall observation that API RP 2A does a good, somewhat conservative job of determining platform performance.

The Lili work shown here involves three platforms (one survival platform, two damaged platforms), thus representing a smaller sample size compared to Andrew calculation. The jacket bias factor is higher than the Andrew results. This can be attributed to one damaged platform (EI

231), in which the calculation shows the maximum base shear already exceeds the jacket collapse strength. In reality, this platform is left standing with only several damaged members.

The foundation lateral strength bias factor for Lili is smaller than the Andrew results (mean value of 1.12 versus 1.28). This can be attributed to the fact that no foundation damage was observed after Lili, thus no significant information is fed into the Bayesian updating procedure. This creates a minor change after the Bayesian updating when compared to the prior distribution (mean value of 1.0). The combined bias factor for foundation lateral strength is close to the Andrew results, further indicating the weighting on the Lili information is minor.

The platform capacities, hindcast metocean data and other useful information for the evaluated Lili platforms are listed in Table 3.6.

Table 3.4 – Bias Factor Mean and COV for Three Lili Platforms

SS 269	Damage I	Bj	1.08	0.20
		Bfl	1.10	0.22
		Bfa	1.37	0.20
EI 231	Damage I	Bj	1.16	0.22
		Bfl	1.08	0.25
		Bfa	1.36	0.22
EI 225	Survival	Bj	1.09	0.20
		Bfl	1.10	0.22
		Bfa	1.37	0.19

Table 3.5 – Calculated Strength Bias Factors from Hurricane Andrew, Lili and Combined

	Andrew		**Lili**		**Combined**	
Bias Factor	**Mean**	**COV**	**Mean**	**COV**	**Mean**	**COV**
Jacket	1.09	0.12	1.24	0.13	1.18	0.10
Foundation Lateral	1.28	0.17	1.12	0.22	1.31	0.17
Foundation Axial	1.35	0.20	1.37	0.19	1.32	0.18

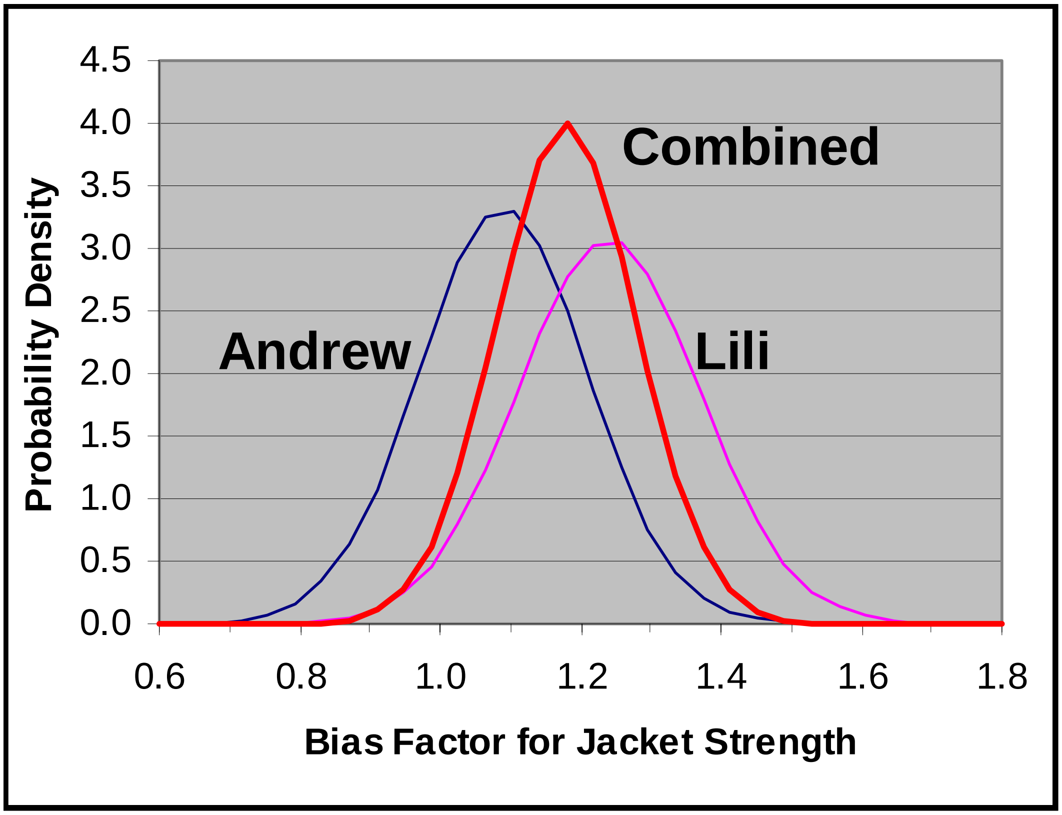


Figure 3.1 – Bias Curves for Andrew, Lili and Combined

Table 3.6 – Platform Information Summary for Hurricane Lili Bias Factor Calculation (analyzed platforms highlighted in yellow)

Platform	Category	Jacket Resistance Damage (kip)	Jacket Resistance Ultimate (kip)	Foundation Lateral Resistance (kip)	Foundation Axial Resistance (kip)	Max. Expected Base Shear (kip)	h_{max} (ft)	Height of Deck (ft)	Hs (ft)	Current (knots)	Tp (sec)	Wave Dir (deg)	Hs (ft)	Current (knots)	Tp (sec)	Wave Dir (deg)	Hs (ft)	Current (knots)	Tp (sec)	Wave Dir (deg)	C1	C2	C3	C4	Logic
SS204A	Damage I						47.2		28.0	0.8	13.0	120.9	26.7	0.6	12.5	138.4	25.0	0.5	11.8	152.5					
EI322A-PRD	Failure I						59.4	75	35.3	0.6	13.6	101.8	31.7	0.6	12.8	160.8	27.2	0.6	12.1	176.0					
EI231CA	Damage I	669	1102	1196	1244	1345	48.7		28.9	3.3	12.8	117.5	26.1	3.7	11.7	152.3	23.4	3.4	11.4	167.5	0.218	6.245	2.059	0	$669*bj<S<1102*b_j$ AND $669*bj<1196*b_{fl}$ AND $669*bj<1244*b_{fa}$
EI231CB	Damage I						48.7		28.9	0.7	12.8	117.5	26.1	0.7	11.7	152.3	23.4	0.8	11.4	167.5					
EI252C/L	Survival	6264	8412	8770	9307	5516	49.7	45	29.5	2.3	12.9	106.5	26.7	1.7	12.1	164.1	23.3	1.7	11.4	176.1	0.806	8.502	2.07	9.81E-03	S<6264*bj AND S<8770*bfl AND S<9307*bfa
SS114 15	Damage I																								
EI330A	Damage I						48.8		29.0	1.1	13.5	5.6	26.0	1.1	12.9	272.1	22.2	1.2	12.6	229.6					
EI330B	Damage I						48.8		29.0	1.1	13.5	5.6	26.0	1.1	12.9	272.1	22.2	1.2	12.6	229.6					
EI337A	Damage I						47.5		28.2	1.1	13.6	2.6	25.9	1.1	12.9	290.8	22.3	1.2	12.7	240.0					
EI314A	Damage I						47.6		28.3	0.7	13.8	12.4	26.2	0.7	13.0	307.4	22.4	0.7	12.7	239.3					
EI309C	Damage I						49.2		29.2	0.6	13.5	24.8	25.5	0.6	12.9	270.3	21.6	0.6	12.6	219.7					
EI273A	Damage I						51.3		30.5	2.0	13.6	57.2	26.5	1.8	12.8	221.1	23.4	1.4	12.2	198.7					
SS269A	Damage I	2666	3998	4165	3499	3250	56.0	34	33.2	2.2	13.2	115.7	30.4	2.2	12.7	147.1	26.9	2.0	11.6	163.5	0.308	8.601	2.108	2.54E-03	$2666*bj<S<3998*b_j$ AND $2666*bj<4165*b_{fl}$ AND $2666*bj<3499*b_{fa}$
EI215D01	Damage II						47.5		28.2	2.6	12.9	114.5	26.2	3.2	11.8	155.2	23.4	2.5	11.4	170.2					
EI324A	Failure I						58.5		34.7	0.7	13.5	110.6	30.1	0.7	12.8	180.5	26.0	0.7	12.1	185.6					
EI295A-PRD	Damage I						53.5		31.8	2.2	13.9	64.3	28.0	2.2	12.9	193.3	24.4	2.0	11.9	193.5					
EI176 A-VALVE	Damage I						41.5		24.6	0.9	12.5	105.9	23.0	0.8	11.0	161.6	20.3	0.8	10.7	174.2					
EI275A	Failure I						53.1	74	31.6	1.4	13.3	88.9	29.0	1.2	12.6	163.6	24.6	0.9	11.6	180.0					
EI276B-AUX	Damage I						54.3	59	32.2	1.4	13.2	302.4	29.3	1.2	12.6	310.8	25.1	0.9	11.6	316.9					

Definition	Survival	No damage observed in jacket or foundation
	Failure I	Jacket failed, but foundation remains intact
	Failure II	Failure is known, but not specifically attributed to jacket or foundation
	Damage I	Known damage to jacket, and foundation remains intact
	Damage II	Damage is known, but not specifically attributed to jacket or foundation

S is the base shear of jacket (a probabilistic quantity), caused by hurrican Andrew

3.3 Conclusions

As previously discussed, Figure 3.1 shows the overall results of the evaluation in terms of the bias factor computed for Lili, Andrew and for the combination of the two. The center of each distribution is the approximate value of the mean bias factor, which was approximately 1.2 for Lili and 1.1 for Andrew – both reflecting that API RP 2A is doing a good, conservative job of estimating platform performance, with conservatism in the range of 10 to 20 percent. Also shown is a combined curve where the results of this evaluation for Lili were combined with the 1994 evaluation of Andrew, resulting in a bias factor of a little less than 1.2 (note that these comparisons are nonlinear and cannot just simply be added and averaged). In conclusion, the API RP 2A approach provides for well designed platforms in terms of response to hurricanes as determined by analytical studies for both Lili and Andrew.

4.0 References

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6. Puskar, F.J., Ku, A., Sheppard, R.E., Hurricane Lili's Impact on Fixed Platforms and Calibration of Platform Performance to API RP 2A, OTC 16802, 2004.
7. Aggarwal, R.K., Dolan, D.K., Cornell, C.A., Development of Bias in Analytical Predictions Based on Behavior of Platforms During Hurricanes, OTC 8077, 1996.
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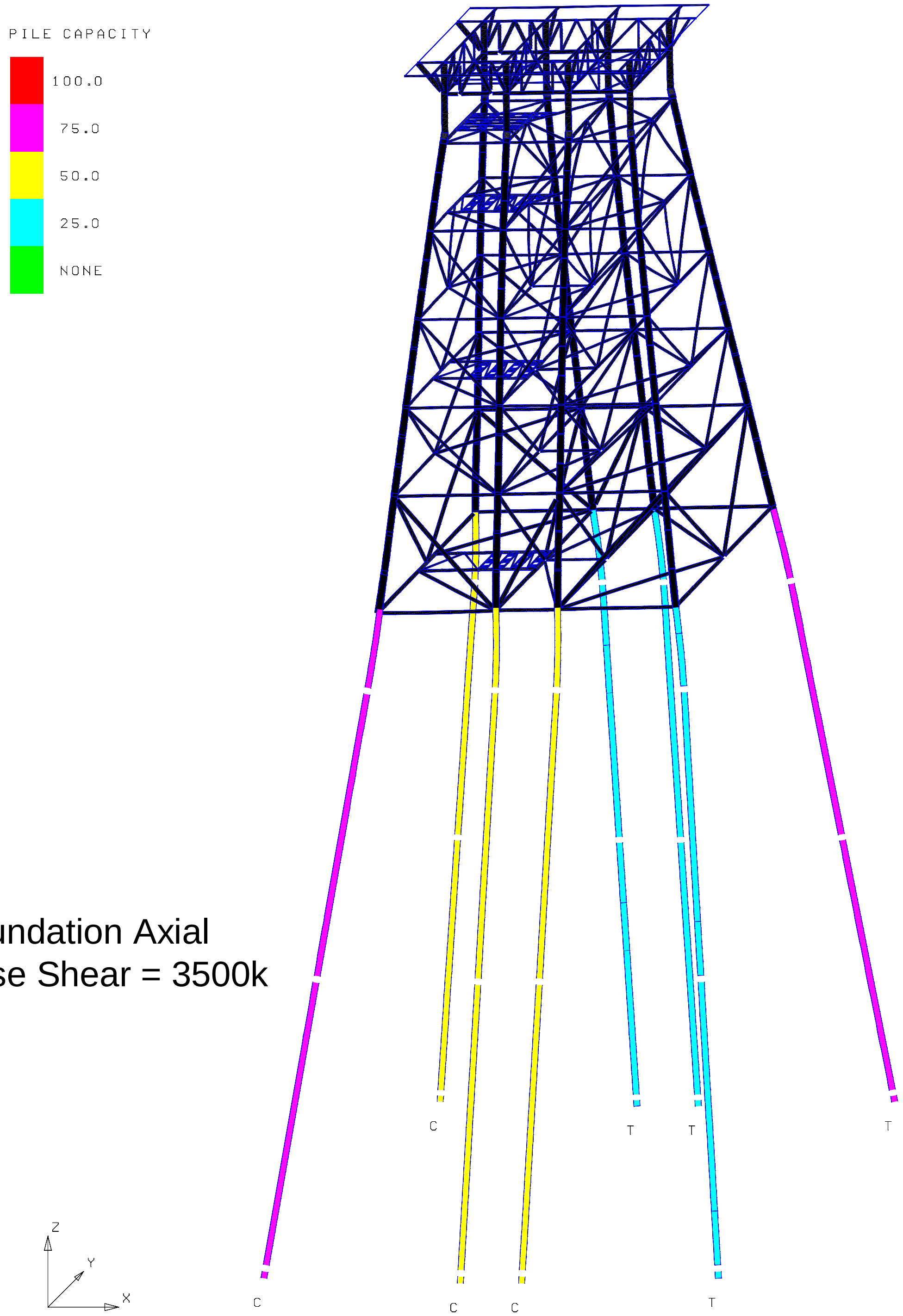
Appendix A

Platform Reliability Process - Detailed Information

Sample Output from Jacket Push-Over Analysis



Foundation Axial
Base Shear = 3500k

Figure A-1: Inelastic/Failure Events – Platform EI 231 CA

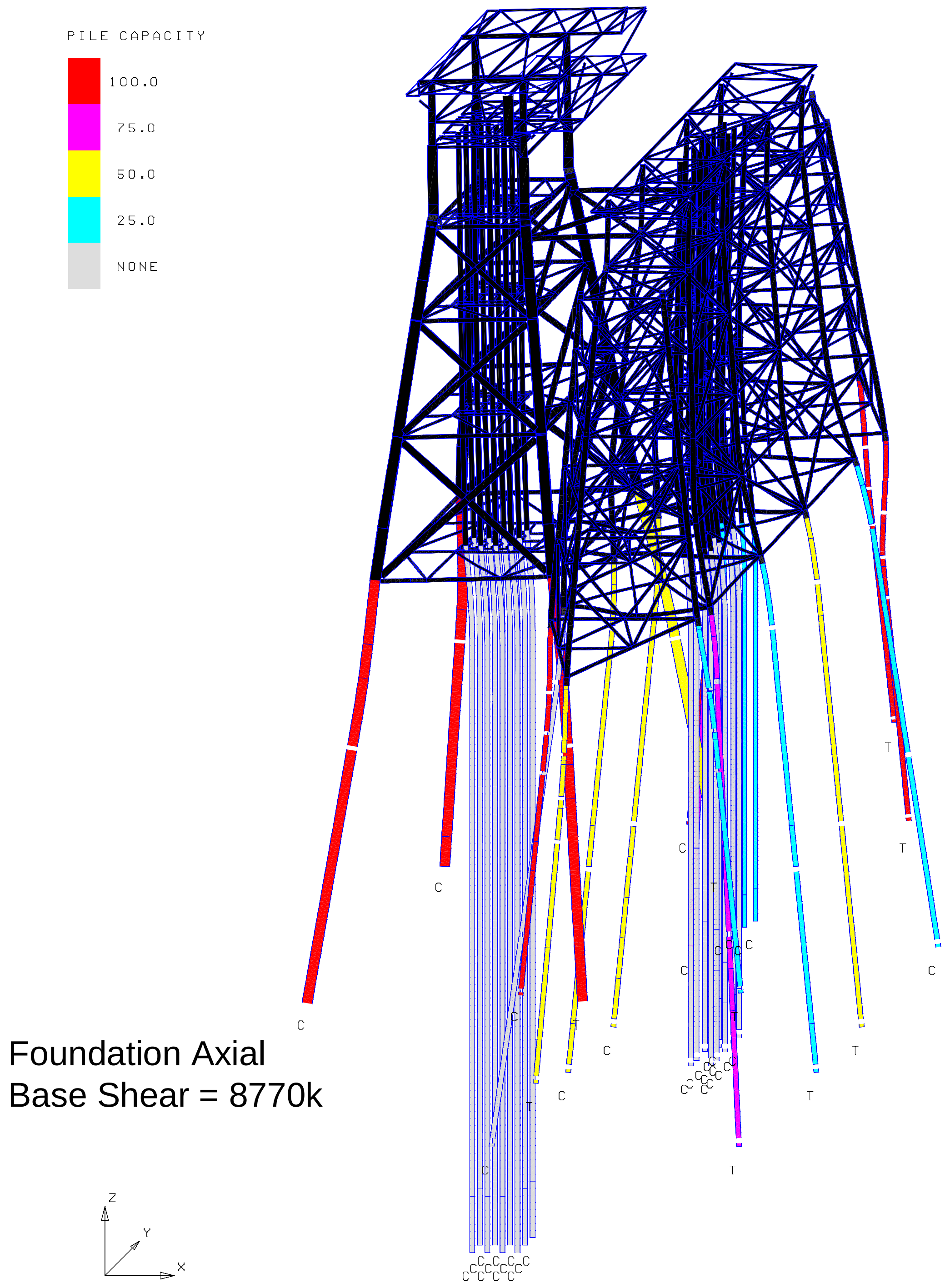


Figure A-2: Inelastic/Failure Events – Platform EI 252 C/L

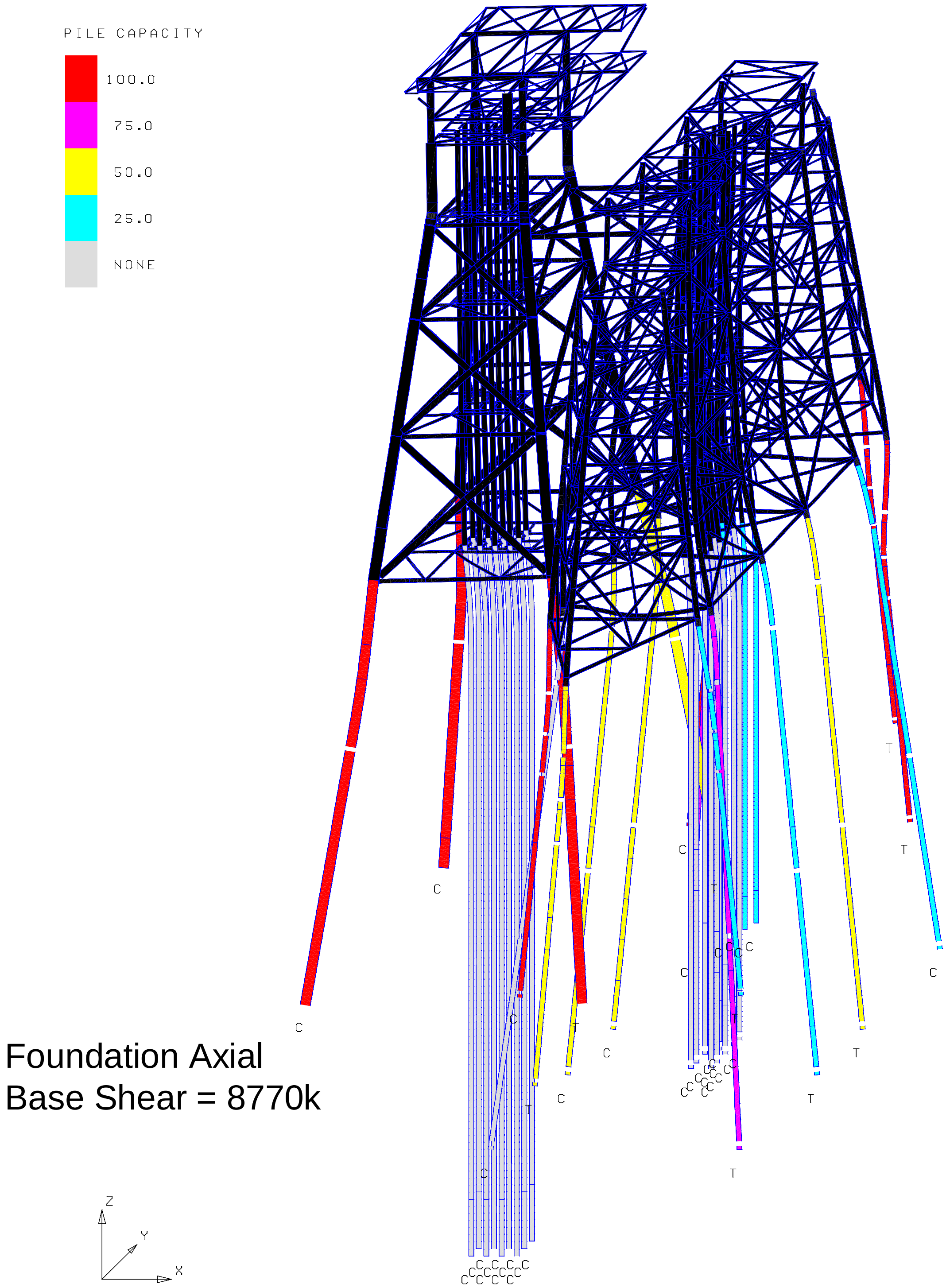


Figure A-3: Inelastic/Failure Events – Platform SS 269 A

Bayesian Updating MathCad Worksheet for Platform EI 231

This Worksheet Calculates the Posterior Distributions of Bias Factors

Table of Contents

1.0: Input of Structural Reliabiltiy Results

Bj = Bias factor for jacket strength
Bfl = Bias factor for foundation strength - Lateral
Bfa = Bias factor for foundation strength - Axial

Define Ranges of Bias Factors

$t := 11$

$$Bj := \left| \begin{array}{l} \text{for } i \in 0..t \\ \quad B_i \leftarrow .6 + (i+1)\cdot .1 \\ B \end{array} \right. \qquad Bfl := \left| \begin{array}{l} \text{for } i \in 0..t \\ \quad B_i \leftarrow .6 + (i+1)\cdot .1 \\ B \end{array} \right. \qquad Bfa := \left| \begin{array}{l} \text{for } i \in 0..t-1 \\ \quad B_i \leftarrow .9 + (i+1)\cdot .1 \\ B \end{array} \right.$$

Bj =

	0
0	0.7
1	0.8
2	0.9
3	1
4	1.1
5	1.2
6	1.3
7	1.4
8	1.5
9	1.6
10	1.7
11	1.8

Bfl =

	0
0	0.7
1	0.8
2	0.9
3	1
4	1.1
5	1.2
6	1.3
7	1.4
8	1.5
9	1.6
10	1.7
11	1.8

Bfa =

	0
0	1
1	1.1
2	1.2
3	1.3
4	1.4
5	1.5
6	1.6
7	1.7
8	1.8
9	1.9
10	2

The following table contains the failure probabilities calculated in STRUREL. These probabilities are the likelihood function for the Bayesian updating procedure.

$n := 1584$

$P2 :=$

Worksheet

1

$P2 =$

	0	1	2	3
0	1	"bfl"	"bfa"	"Beta Low"
1	0.7	0.7	1	-3.146
2	0.7	0.7	1.1	-3.171
3	0.7	0.7	1.2	-3.18
4	0.7	0.7	1.3	-3.184
5	0.7	0.7	1.4	-3.185
6	0.7	0.7	1.5	-3.186
7	0.7	0.7	1.6	-3.186
8	0.7	0.7	1.7	-3.186
9	0.7	0.7	1.8	-3.186
10	0.7	0.7	1.9	-3.186
11	0.7	0.7	2	-3.186
12	0.7	0.8	1	-3.334
13	0.7	0.8	1.1	-3.369
14	0.7	0.8	1.2	-3.382
15	0.7	0.8	1.3	-3.388

2.0: Determine Marginal Posterior Distributions

The posterior distribution is the product of prior distribution and the likelihood function:

f''(bj,bfl,bfa) = f'(bj,bfl,bfa)*lk(bj,bfl,bfa)

```
$Pp :=$
    for $i \in 1..n$
        $Pp_i \leftarrow (P2_{i,7})\cdot(dnorm(P2_{i,0},1,.3)\cdot dnorm(P2_{i,1},1,.3)\cdot dnorm(P2_{i,2},1.3,.3))$
    $Pp$
```

Note: Pp is the posterior distribution f''(bj,bfl,bfa)

The individual (marginal) posterior distribution is obtained by integrating out the other variables. Numerical integration is performed using the Trapozoidal Rule.

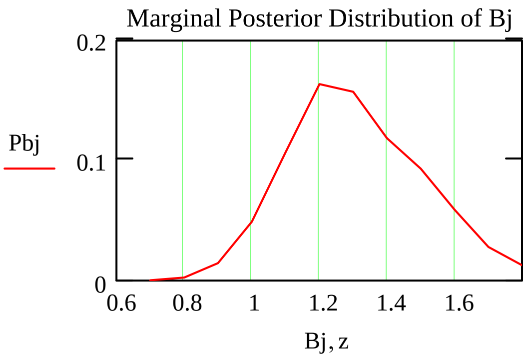
2.1 Determine Posterior Distribution of f''(bj)

For f''(bj), first integrate bfl out, and then bfa.

$k := 0 \quad s := 0 \quad d := 0 \quad ds := 0 \quad i := 0$

```
$Pbbj :=$
    for $i \in 0..t$
        $Pb_i \leftarrow 0$
    for $j \in 0..t$
        for $k \in 0..t-1$
            for $s \in 0..t$
                for $i \in 0..n$
                    if $P2_{i,0} = Bj_j$
                        if $P2_{i,2} = Bfa_k$
                            $Pb_s \leftarrow Pp_i$ if $P2_{i,1} = Bfl_s$
                            $1$
                        $1$
                $1$
            $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
            $ps_{j,k} \leftarrow 0.05\cdot(Pb_0 + Pb_t + 2\cdot d)$
        $1$
    $ps$
```

```
$Pbj :=$
    for $j \in 0..t$
        $ds \leftarrow \sum_{k=0}^{9} Pbbj_{j,k}$
        $1$
        $pss_j \leftarrow 0.05\cdot(Pbbj_{j,0} + Pbbj_{j,10} + 2\cdot ds)$
    $pss$
```

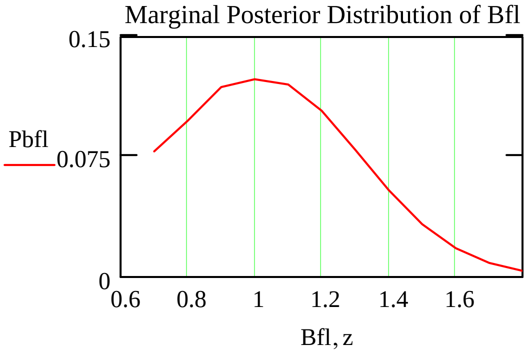


2.2 Determine Posterior Distribution of f"(bfl)

For f"(bfl), first integrate bj out, and then bfa

```
$Pbbfl :=$
  for $i \in 0 .. t$
    $Pb_i \leftarrow 0$
  for $j \in 0 .. t$
    for $k \in 0 .. t-1$
      for $s \in 0 .. t$
        for $i \in 0 .. n$
          if $P2_{i,1} = Bfl_j$
            if $P2_{i,2} = Bfa_k$
              $Pb_s \leftarrow Pp_i$ if $P2_{i,0} = Bj_s$
              1
            1
          1
        $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
        $ps_{j,k} \leftarrow 0.05 \cdot \left(Pb_0 + Pb_t + 2 \cdot d\right)$
      1
  ps
```

```
$Pbfl :=$
  for $j \in 0 .. t$
    $ds \leftarrow \sum_{k=0}^{9} Pbbfl_{j,k}$
    1
    $pss_j \leftarrow 0.05 \cdot \left(Pbbfl_{j,0} + Pbbfl_{j,10} + 2 \cdot ds\right)$
  pss
```

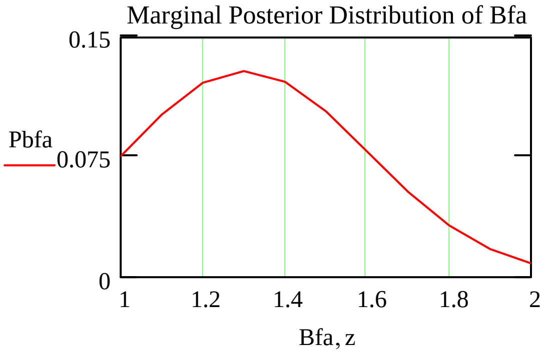


2.3 Determine Posterior Distribution of f"(bfa)

For f"(bfa), first integrate bj out, and then bfl.

```
Pbbfa := | for  i ∈ 0 .. t
         |   $Pb_i \leftarrow 0$
         | for  j ∈ 0 .. t − 1
         |   for  k ∈ 0 .. t
         |     for  s ∈ 0 .. t
         |       for  i ∈ 0 .. n
         |         if  $P2_{i,2} = Bfa_j$
         |           if  $P2_{i,1} = Bfl_k$
         |             $Pb_s \leftarrow Pp_i$  if  $P2_{i,0} = Bj_s$
         |             1
         |           1
         |         1
         |       $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
         |       $ps_{j,k} \leftarrow 0.05 \cdot (Pb_0 + Pb_t + 2 \cdot d)$
         |     1
         | ps
```

```
Pbfa := | for  j ∈ 0 .. t − 1
        |   $ds \leftarrow \sum_{k=0}^{10} Pbbfa_{j,k}$
        |   1
        |   $pss_j \leftarrow 0.05 \cdot (Pbbfa_{j,0} + Pbbfa_{j,11} + 2 \cdot ds)$
        | pss
```



Note that the proper magnitude (scaling factor) of the above posterior distributions has not been determined yet. The magnitude of these distributions has to be normalized such that the areas of these curves are 1.0. This normalization will be performed as follows in which a log-normal distribution is fitted to each of these distributions.

3.0: Best Fit to Calculated Distributions and Determine Mean/Standard Deviations

Use the MathCad function "genfit" to find the best-fit log-normal distribution. The following three parameters will be identified:

g0 : Mean value of ln(z)
g1 : Standard deviation of ln(z)
g2 : A scaling factor to shift the log-normal distribution to fit the calculated posterior distribution

Function defined in the next expression is composed as follows:

1st element : Log-normal distribution
2nd element : Partial derivative of log-normal distribution w.r.t. g0
3rd element : Partial derivative of log-normal distribution w.r.t. g1
4th element : Partial derivative of log-normal distribution w.r.t. g2

$$
\mathrm{Fl}(z,g) := \begin{bmatrix}
\dfrac{g_2}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]} \\[2ex]
\dfrac{g_2}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{z-g_0}{g_1}\right)^2\right]}\cdot\dfrac{\left(\ln(z)-g_0\right)}{\left(g_1\right)^2} \\[2ex]
\dfrac{\dfrac{\left[e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}\right]\cdot\left(z-g_0\right)^2\cdot g_2}{\left(g_1\right)^2}\cdot\left[-e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}\right]}{\left(g_1\right)^2\cdot z} \\[2ex]
\dfrac{1}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}
\end{bmatrix}
$$

3.1 Best fit of posterior distribution of bj

$$vgl := \begin{pmatrix} 0.25 \\ 0.15 \\ 0.05 \end{pmatrix}$$

Inital guess on g0, g1 and g2

$$Tl := genfit(Bj, Pbj, vgl, Fl)$$

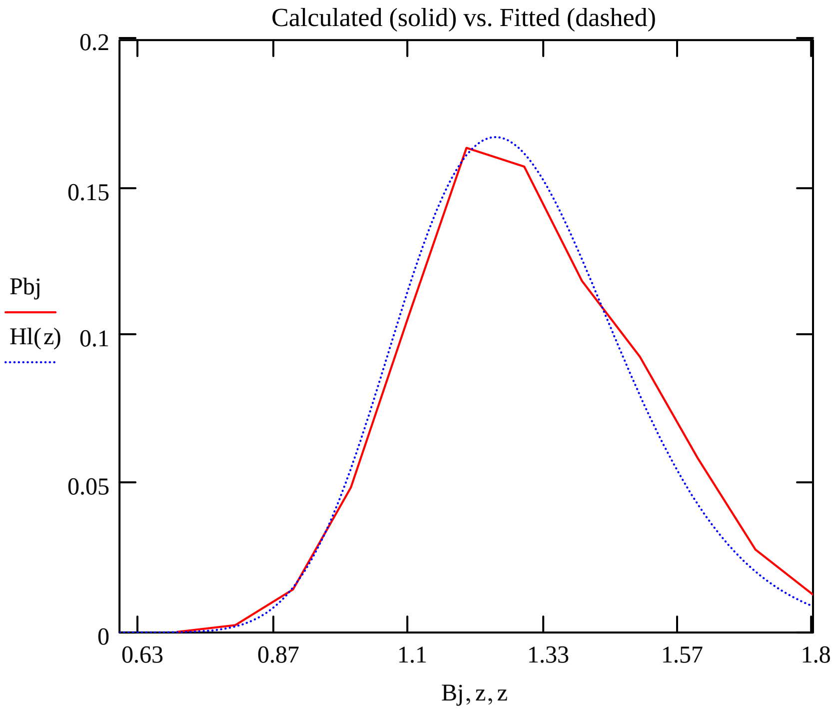
$$Tl = \begin{pmatrix} 0.246 \\ 0.15 \\ 0.08 \end{pmatrix}$$

Best fit solution

Calculate mean value and cov of fitted log-normal distribution

$$Hl(z) := Fl(z, Tl)_0 \quad hl(z) := dlnorm\left(z, Tl_0, Tl_1\right) \cdot Tl_2$$

$$mean := e^{\left[Tl_0 + \frac{\left(Tl_1\right)^2}{2}\right]} \qquad COV := Tl_1$$



Bj bias factor

mean = 1.293

COV = 0.15

3.2 Best Fit of Posterior Distribution bfl

$$vgl := \begin{pmatrix} 0.2 \\ 0.27 \\ 0.15 \end{pmatrix}$$

Initial guess on g0, g1 and g2

$Tl := genfit(Bfl, Pbfl, vgl, Fl)$

$$Tl = \begin{pmatrix} 0.043 \\ 0.276 \\ 0.094 \end{pmatrix}$$

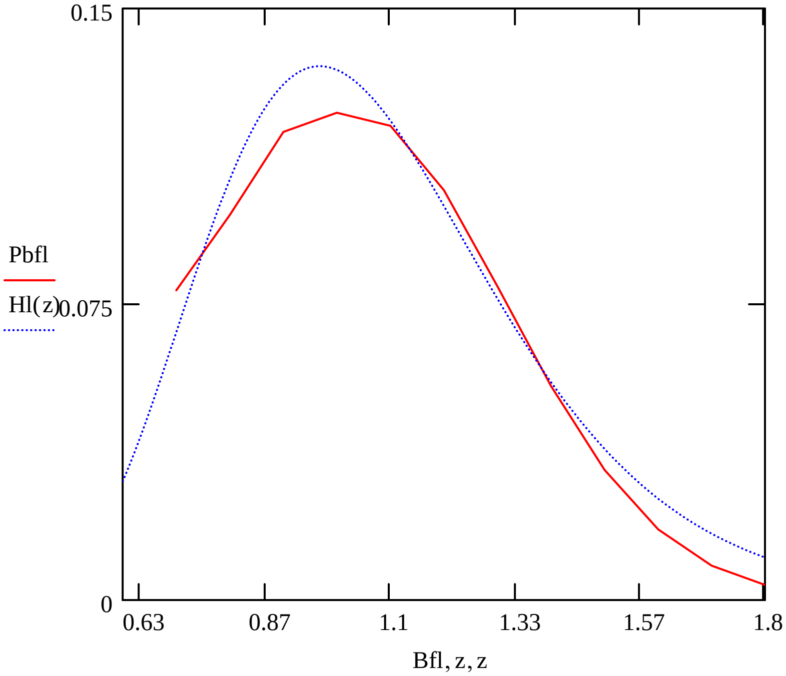
Best fit solutions

Calculate mean value and cov of fitted log-normal distribution

$Hl(z) := Fl(z, Tl)_0$ $hl(z) := dlnorm\left(z, Tl_0, Tl_1\right)\cdot Tl_2$

$$mean := e^{\left[Tl_0 + \frac{\left(Tl_1\right)^2}{2}\right]} \qquad COV := Tl_1$$

Calculated (solid) vs. Fitted (dashed)



Bfl bias factor

mean = 1.085

COV = 0.276

3.3 Best fit on Posterior Distribution of bfa

$$vgl := \begin{pmatrix} 0.3 \\ .2 \\ 0.085 \end{pmatrix}$$

Initial guess on g0, g1 and g2

$$Tl := genfit(Bfa, Pbfa, vgl, Fl)$$

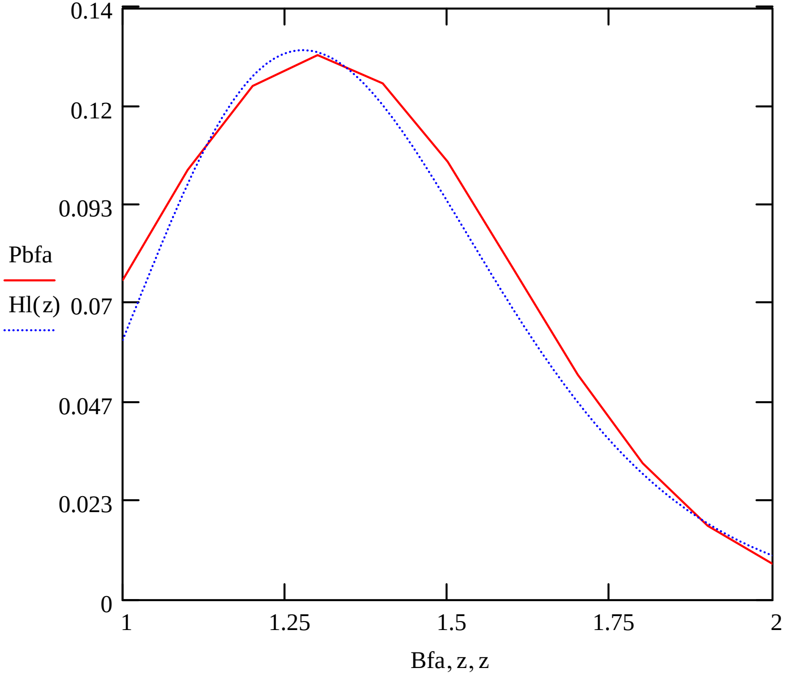
$$Tl = \begin{pmatrix} 0.285 \\ 0.2 \\ 0.085 \end{pmatrix}$$

Best fit solutions

$$Hl(z) := Fl(z, Tl)_0 \quad hl(z) := dlnorm\left(z, Tl_0, Tl_1\right) \cdot Tl_2$$

$$mean := e^{\left[Tl_0 + \frac{\left(Tl_1\right)^2}{2}\right]} \qquad COV := Tl_1$$

Calculated (solid) vs. Fitted (dashed)



Bfa bias factor

mean = 1.356

COV = 0.2

4.0: Marginal Likelihood Functions

The likelihood function, lk(bj,bfl,bfa), has been used in previous sections in determining the posterior distributions of the bias factors. Note that lk(bj,bfl,bfa) is the structural reliability solution from STRUREL and is a function of all three bias factors, bj, bfl and bfa. lk(bj,bfl,bfa) is termed the "joint likelihood function".

For reference and comparison to the Andrew Phase 2 report, the "marginal likelihood function" is also calculated. The calculation of marginal likelihood function, for example lk(bj), is calculated by integrating the bias factors bfl and bfa out of lk(bj,bfl,bfa).

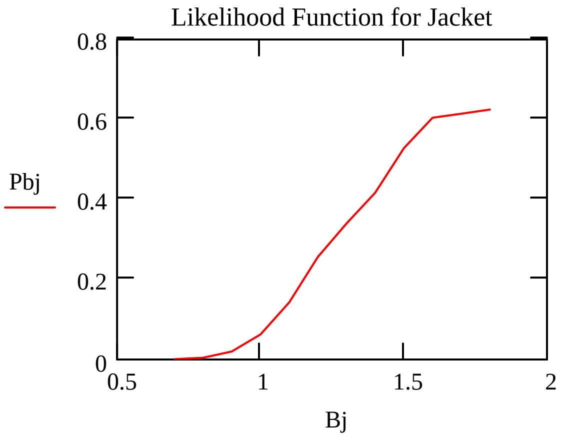
Note that the calculation in this section does not directly relate to the posterior distribution of the bias factors. These marginal likelihood functions are only calculated for reference purposes only.

4.1 Marginal Likelihood Function lk(bj)

```
Pbj := | for  i ∈ 0 .. t
       |   $Pb_i \leftarrow 0$
       | for  j ∈ 0 .. t
       |   for  i ∈ 1 .. n
       |     $Pb_j \leftarrow Pb_j + \left(P2_{i,7}\right)$  if  $P2_{i,0} = Bj_j$
       | $\frac{Pb}{100}$
```

Pbj =

	0
0	$4.186 \cdot 10^{-4}$
1	$4.004 \cdot 10^{-3}$
2	0.02
3	0.063
4	0.143
5	0.256
6	0.34
7	0.417
8	0.528
9	0.604
10	0.614
11	0.625

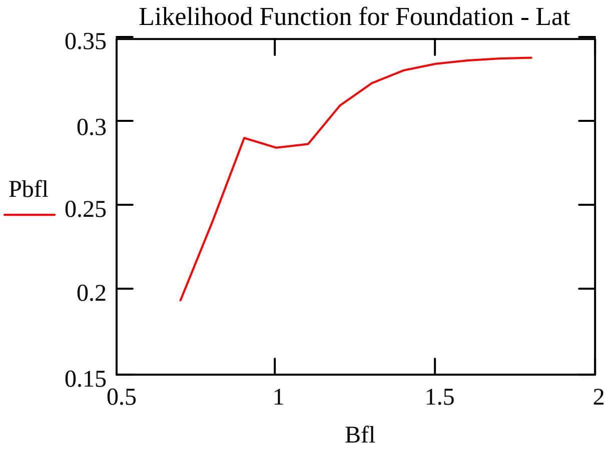


4.2 Marginal Likelihood Function lk(bfl)

```
Pbfl := | for  $i \in 0..t$
        |   $Pb_i \leftarrow 0$
        | for  $j \in 0..t$
        |   for  $i \in 1..n$
        |     $Pb_j \leftarrow Pb_j + \left(P2_{i,7}\right)$  if  $P2_{i,1} = Bfl_j$
        | $Pb \cdot .1 \cdot .1$
```

Pbfl =

	0
0	0.194
1	0.241
2	0.291
3	0.285
4	0.287
5	0.31
6	0.324
7	0.331
8	0.335
9	0.337
10	0.338
11	0.339

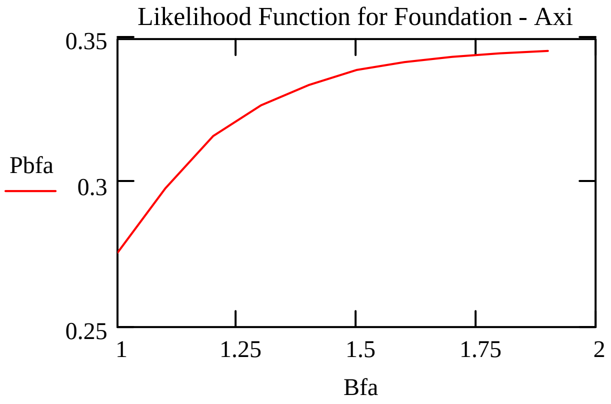


4.3 Marginal Likelihood Function lk(bfa)

```
Pbfa := | for  $i \in 0..t-2$
        |   $Pb_i \leftarrow 0$
        | for  $j \in 0..t-2$
        |   for  $i \in 1..n$
        |     $Pb_j \leftarrow Pb_j + \left(P2_{i,7}\right)$  if  $P2_{i,2} = Bfa_j$
        | $Pb \cdot .1 \cdot .1$
```

Pbfa =

	0
0	0.276
1	0.298
2	0.316
3	0.327
4	0.334
5	0.339
6	0.342
7	0.344
8	0.345
9	0.346



Bayesian Updating MathCad Worksheet for Platform EI 252 CL

This Worksheet Calculates the Posterior Distributions of Bias Factors

Table of Contents

1.0: Input of Structural Reliabiltiy Results

Bj = Bias factor for jacket strength
Bfl = Bias factor for foundation strength - Lateral
Bfa = Bias factor for foundation strength - Axial

Define Ranges of Bias Factors

$t := 12$

```
Bj := | for  i ∈ 0 .. t
      |   B_i ← .5 + (i + 1)·.1
      | B
```

```
Bfl := | for  i ∈ 0 .. t
       |   B_i ← .5 + (i + 1)·.1
       | B
```

```
Bfa := | for  i ∈ 0 .. t − 2
       |   B_i ← .9 + (i + 1)·.1
       | B
```

Bj =

	0
0	0.6
1	0.7
2	0.8
3	0.9
4	1
5	1.1
6	1.2
7	1.3
8	1.4
9	1.5
10	1.6
11	1.7
12	1.8

Bfl =

	0
0	0.6
1	0.7
2	0.8
3	0.9
4	1
5	1.1
6	1.2
7	1.3
8	1.4
9	1.5
10	1.6
11	1.7
12	1.8

Bfa =

	0
0	1
1	1.1
2	1.2
3	1.3
4	1.4
5	1.5
6	1.6
7	1.7
8	1.8
9	1.9
10	2

The following table contains the failure probabilities calculated in STRUREL. These probabilities are the likelihood function for the Bayesian updating procedure.

$n := 1859$

$P2 :=$

Worksheet

1

$P2 =$

	0	1	2	3	4	5
0	1	"bfl"	"bfa"	"Beta Low"	"Beta High"	0
1	0.6	0.6	1	1.685	1.685	0.046
2	0.6	0.6	1.1	1.685	1.685	0.046
3	0.6	0.6	1.2	1.685	1.685	0.046
4	0.6	0.6	1.3	1.685	1.685	0.046
5	0.6	0.6	1.4	1.685	1.685	0.046
6	0.6	0.6	1.5	1.685	1.685	0.046
7	0.6	0.6	1.6	1.685	1.685	0.046
8	0.6	0.6	1.7	1.685	1.685	0.046
9	0.6	0.6	1.8	1.685	1.685	0.046
10	0.6	0.6	1.9	1.685	1.685	0.046
11	0.6	0.6	2	1.685	1.685	0.046
12	0.6	0.7	1	1.685	1.685	0.046
13	0.6	0.7	1.1	1.685	1.685	0.046
14	0.6	0.7	1.2	1.685	1.685	0.046
15	0.6	0.7	1.3	1.685	1.685	0.046

2.0: Determine Marginal Posterior Distributions

The posterior distribution is the product of prior distribution and the likelihood function:

f"(bj,bfl,bfa) = f'(bj,bfl,bfa)*lk(bj,bfl,bfa)

```
$Pp :=$ for $i \in 1..n$
    $Pp_i \leftarrow (P2_{i,5})\cdot(dnorm(P2_{i,0},1,.3)\cdot dnorm(P2_{i,1},1,.3)\cdot dnorm(P2_{i,2},1.3,.3))$
  $Pp$
```

Note: Pp is the posterior distribution f"(bj,bfl,bfa)

The individual (marginal) posterior distribution is obtained by integrating out the other variables. Numerical integration is performed using the Trapozoidal Rule.

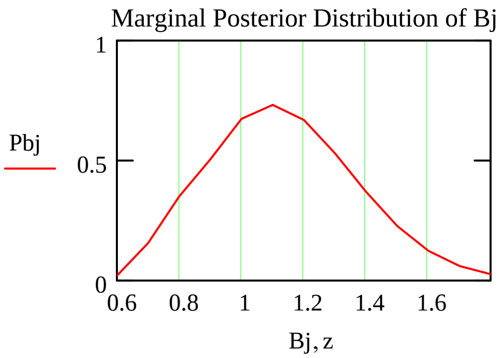
2.1 Determine Posterior Distribution of f"(bj)

For f"(bj), first integrate bfl out, and then bfa.

$k := 0$ $s := 0$ $d := 0$ $ds := 0$ $i := 0$

```
$Pbbj :=$ for $i \in 0..t$
            $Pb_i \leftarrow 0$
          for $j \in 0..t$
            for $k \in 0..t-2$
              for $s \in 0..t$
                for $i \in 0..n$
                  if $P2_{i,0} = Bj_j$
                    if $P2_{i,2} = Bfa_k$
                      $Pb_s \leftarrow Pp_i$ if $P2_{i,1} = Bfl_s$
                      $1$
                    $1$
                $1$
              $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
              $ps_{j,k} \leftarrow 0.05\cdot(Pb_0 + Pb_t + 2\cdot d)$
            $1$
          $ps$
```

```
$Pbj :=$ for $j \in 0..t$
           $ds \leftarrow \sum_{k=0}^{9} Pbbj_{j,k}$
           $1$
           $pss_j \leftarrow 0.05\cdot(Pbbj_{j,0} + Pbbj_{j,10} + 2\cdot ds)$
         $pss$
```

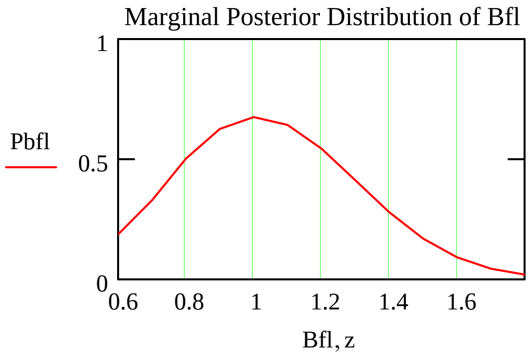


2.2 Determine Posterior Distribution of f"(bfl)

For f"(bfl), first integrate bj out, and then bfa

```
Pbbfl := for  $i \in 0..t$
             $Pb_i \leftarrow 0$
         for  $j \in 0..t$
             for  $k \in 0..t-2$
                 for  $s \in 0..t$
                     for  $i \in 0..n$
                         if  $P2_{i,1} = Bfl_j$
                             if  $P2_{i,2} = Bfa_k$
                                 $Pb_s \leftarrow Pp_i$  if  $P2_{i,0} = Bj_s$
                                 1
                             1
                         1
                     $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
                     $ps_{j,k} \leftarrow 0.05 \cdot (Pb_0 + Pb_t + 2 \cdot d)$
                 1
         ps
```

```
Pbfl := for  $j \in 0..t$
            $ds \leftarrow \sum_{k=0}^{9} Pbbfl_{j,k}$
            1
            $pss_j \leftarrow 0.05 \cdot (Pbbfl_{j,0} + Pbbfl_{j,10} + 2 \cdot ds)$
        pss
```

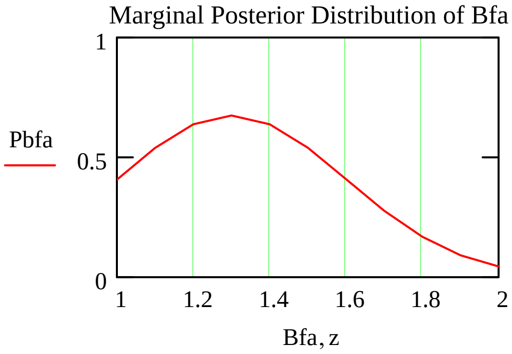


2.3 Determine Posterior Distribution of f"(bfa)

For f"(bfa), first integrate bj out, and then bfl.

```
$Pbbfa :=$
  for $i \in 0..t$
    $Pb_i \leftarrow 0$
  for $j \in 0..t-2$
    for $k \in 0..t$
      for $s \in 0..t$
        for $i \in 0..n$
          if $P2_{i,2} = Bfa_j$
            if $P2_{i,1} = Bfl_k$
              $Pb_s \leftarrow Pp_i$ if $P2_{i,0} = Bj_s$
              1
            1
          1
        $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
        $ps_{j,k} \leftarrow 0.05 \cdot (Pb_0 + Pb_t + 2 \cdot d)$
      1
  ps
```

```
$Pbfa :=$
  for $j \in 0..t-2$
    $ds \leftarrow \sum_{k=0}^{11} Pbbfa_{j,k}$
    1
    $pss_j \leftarrow 0.05 \cdot (Pbbfa_{j,0} + Pbbfa_{j,12} + 2 \cdot ds)$
  pss
```



Note that the proper magnitude (scaling factor) of the above posterior distributions has not been determined yet. The magnitude of these distributions has to be normalized such that the areas of these curves are 1.0. This normalization will be performed as follows in which a log-normal distribution is fitted to each of these distributions.

3.0: Best Fit to Calculated Distributions and Determine Mean/Standard Deviations

Use the MathCad function "genfit" to find the best-fit log-normal distribution. The following three parameters will be identified:

g0 : Mean value of ln(z)
g1 : Standard deviation of ln(z)
g2 : A scaling factor to shift the log-normal distribution to fit the calculated posterior distribution

Function defined in the next expression is composed as follows:

1st element : Log-normal distribution
2nd element : Partial derivative of log-normal distribution w.r.t. g0
3rd element : Partial derivative of log-normal distribution w.r.t. g1
4th element : Partial derivative of log-normal distribution w.r.t. g2

$$
\mathrm{Fl}(z,g) := \left[\begin{matrix}
\dfrac{g_2}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]} \\[2ex]
\dfrac{g_2}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{z-g_0}{g_1}\right)^2\right]}\cdot\dfrac{\left(\ln(z)-g_0\right)}{\left(g_1\right)^2} \\[2ex]
\dfrac{\dfrac{\left[e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}\right]\cdot\left(z-g_0\right)^2\cdot g_2}{\left(g_1\right)^2}\cdot\left[-e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}\right]}{\left(g_1\right)^2\cdot z} \\[2ex]
\dfrac{1}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}
\end{matrix}\right]
$$

3.1 Best fit of posterior distribution of bj

$$vgl := \begin{pmatrix} .31 \\ .22 \\ .5 \end{pmatrix}$$

Inital guess on g0, g1 and g2

$$Tl := \mathrm{genfit}(Bj, Pbj, vgl, Fl)$$

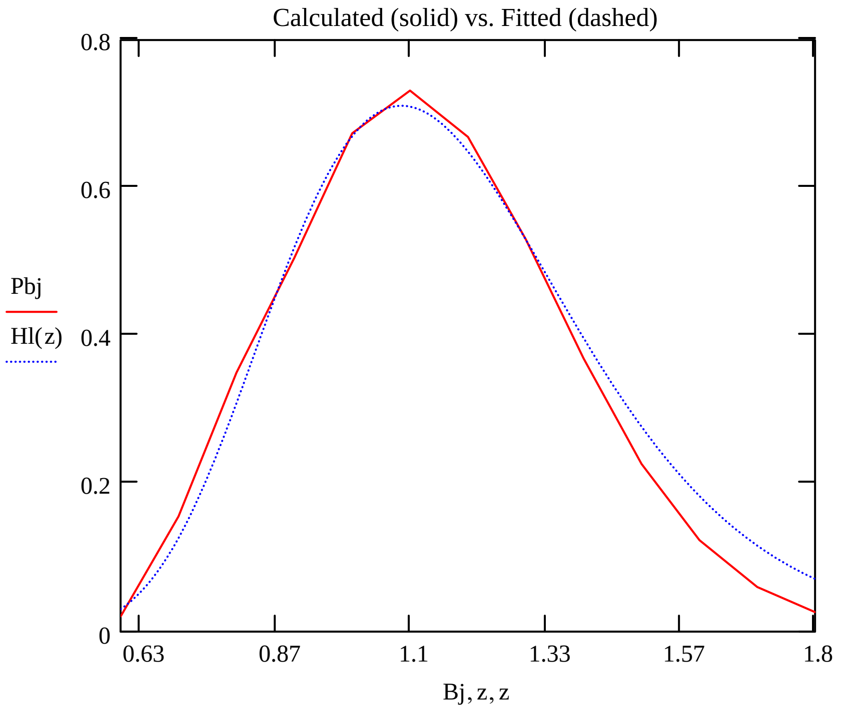
$$Tl = \begin{pmatrix} 0.137 \\ 0.236 \\ 0.469 \end{pmatrix}$$

Best fit solution

Calculate mean value and cov of fitted log-normal distribution

$$Hl(z) := Fl(z, Tl)_0 \quad hl(z) := \mathrm{dlnorm}\left(z, Tl_0, Tl_1\right) \cdot Tl_2$$

$$mean := e^{\left[Tl_0 + \frac{\left(Tl_1\right)^2}{2}\right]} \qquad COV := Tl_1$$



Bj bias factor

$mean = 1.18$

$COV = 0.236$

3.2 Best Fit of Posterior Distribution bfl

$$vgl := \begin{pmatrix} 0.05 \\ 0.25 \\ 0.42 \end{pmatrix}$$

Initial guess on g0, g1 and g2

$$Tl := \text{genfit}(Bfl, Pbfl, vgl, Fl)$$

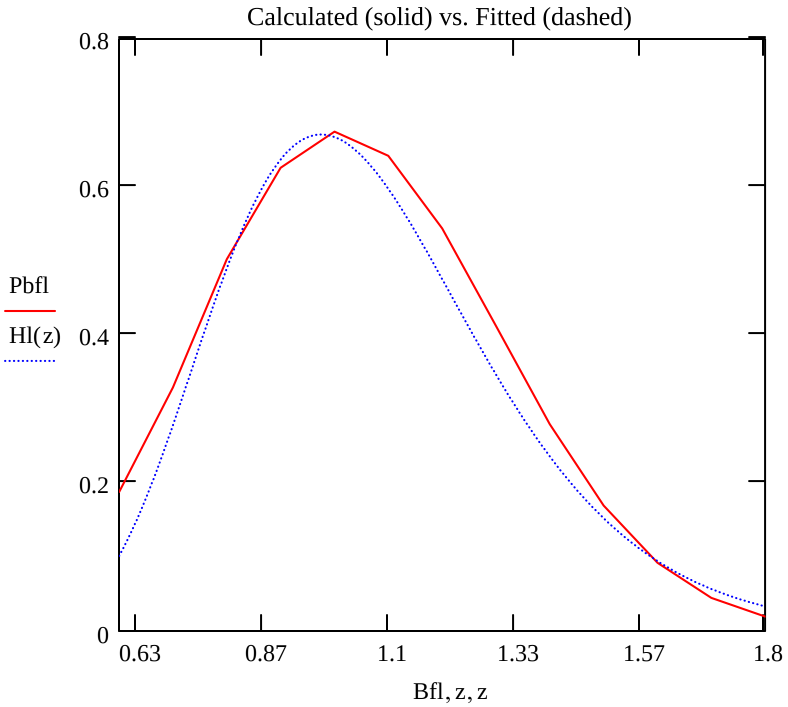
$$Tl = \begin{pmatrix} 0.038 \\ 0.25 \\ 0.423 \end{pmatrix}$$

Best fit solutions

Calculate mean value and cov of fitted log-normal distribution

$$Hl(z) := Fl(z, Tl)_0 \quad hl(z) := \text{dlnorm}\left(z, Tl_0, Tl_1\right) \cdot Tl_2$$

$$mean := e^{\left[Tl_0 + \frac{\left(Tl_1\right)^2}{2}\right]} \qquad COV := Tl_1$$



Bfl bias factor

$mean = 1.071$

$COV = 0.25$

3.3 Best fit on Posterior Distribution of bfa

$$\mathrm{vgl} := \begin{pmatrix} .34 \\ .21 \\ 0.47 \end{pmatrix}$$

Initial guess on g0, g1 and g2

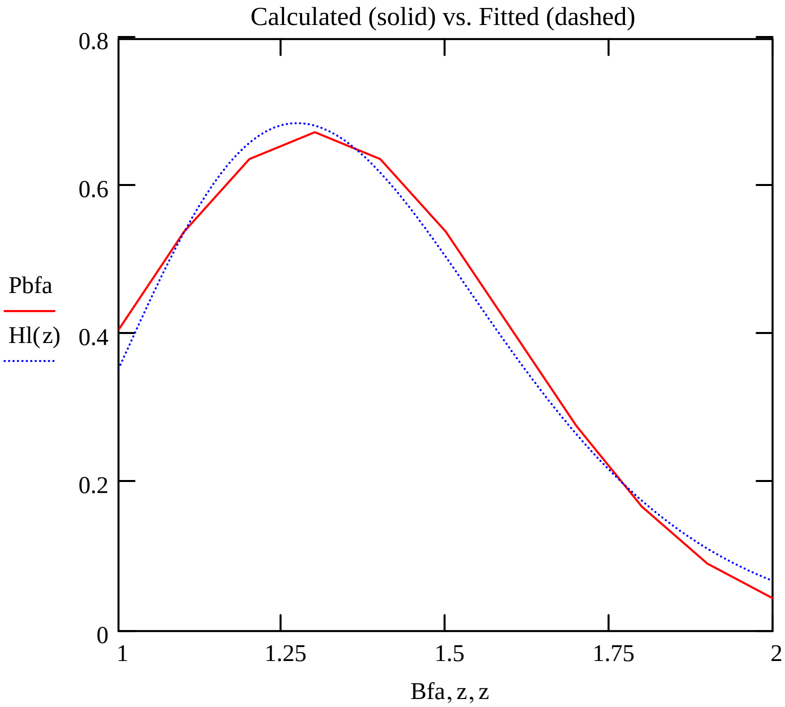
$$\mathrm{Tl} := \mathrm{genfit}(\mathrm{Bfa}, \mathrm{Pbfa}, \mathrm{vgl}, \mathrm{Fl})$$

$$\mathrm{Tl} = \begin{pmatrix} 0.286 \\ 0.21 \\ 0.47 \end{pmatrix}$$

Best fit solutions

$$\mathrm{Hl}(z) := \mathrm{Fl}(z, \mathrm{Tl})_0 \quad \mathrm{hl}(z) := \mathrm{dlnorm}\left(z, \mathrm{Tl}_0, \mathrm{Tl}_1\right) \cdot \mathrm{Tl}_2$$

$$\mathrm{mean} := e^{\left[\mathrm{Tl}_0 + \frac{\left(\mathrm{Tl}_1\right)^2}{2}\right]} \qquad \mathrm{COV} := \mathrm{Tl}_1$$



Bfa bias factor

mean = 1.36

COV = 0.21

4.0: Marginal Likelihood Functions

The likelihood function, lk(bj,bfl,bfa), has been used in previous sections in determining the posterior distributions of the bias factors. Note that lk(bj,bfl,bfa) is the structural reliability solution from STRUREL and is a function of all three bias factors, bj, bfl and bfa. lk(bj,bfl,bfa) is termed the "joint likelihood function".

For reference and comparison to the Andrew Phase 2 report, the "marginal likelihood function" is also calculated. The calculation of marginal likelihood function, for example lk(bj), is calculated by integrating the bias factors bfl and bfa out of lk(bj,bfl,bfa).

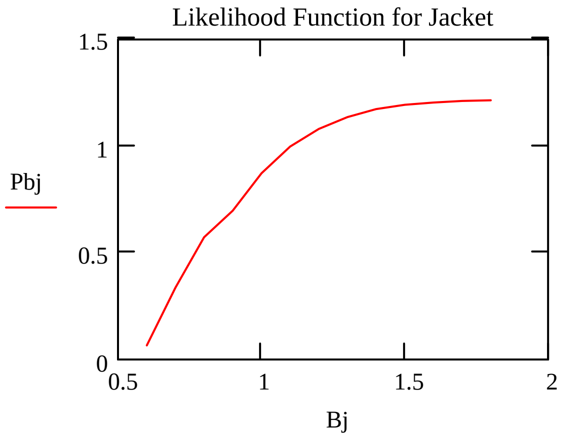
Note that the calculation in this section does not directly relate to the posterior distribution of the bias factors. These marginal likelihood functions are only calculated for reference purposes only.

4.1 Marginal Likelihood Function lk(bj)

```
Pbj := | for  $i \in 0..t$
       |   $Pb_i \leftarrow 0$
       | for  $j \in 0..t$
       |   for  $i \in 1..n$
       |     $Pb_j \leftarrow Pb_j + (P2_{i,5})$  if  $P2_{i,0} = Bj_j$
       | $\frac{Pb}{100}$
```

Pbj =

	0
0	0.066
1	0.336
2	0.573
3	0.697
4	0.872
5	0.998
6	1.08
7	1.136
8	1.173
9	1.193
10	1.204
11	1.212
12	1.215

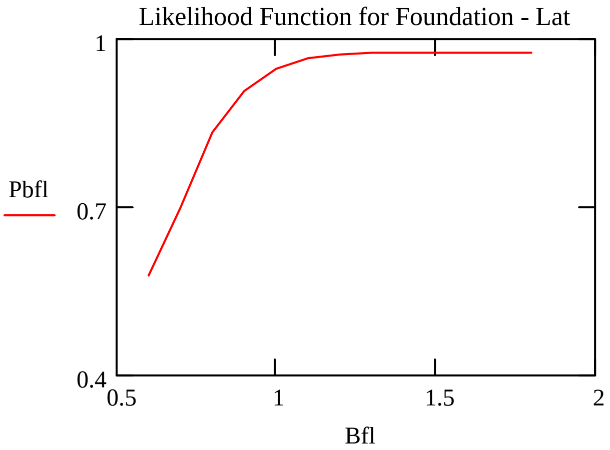


4.2 Marginal Likelihood Function lk(bfl)

```
Pbfl := | for  i ∈ 0 .. t
        |   $Pb_i \leftarrow 0$
        | for  j ∈ 0 .. t
        |   for  i ∈ 1 .. n
        |     $Pb_j \leftarrow Pb_j + (P2_{i,5})$  if  $P2_{i,1} = Bfl_j$
        | Pb·.1·.1
```

Pbfl =

	0
0	0.578
1	0.699
2	0.834
3	0.907
4	0.947
5	0.966
6	0.972
7	0.975
8	0.975
9	0.975
10	0.975
11	0.975
12	0.975

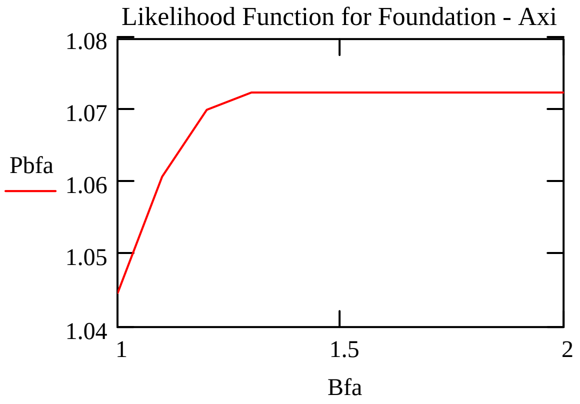


4.3 Marginal Likelihood Function lk(bfa)

```
Pbfa := | for  i ∈ 0 .. t − 2
        |   $Pb_i \leftarrow 0$
        | for  j ∈ 0 .. t − 2
        |   for  i ∈ 1 .. n
        |     $Pb_j \leftarrow Pb_j + (P2_{i,5})$  if  $P2_{i,2} = Bfa_j$
        | Pb·.1·.1
```

Pbfa =

	0
0	1.045
1	1.061
2	1.07
3	1.073
4	1.073
5	1.073
6	1.073
7	1.073
8	1.073
9	1.073
10	1.073



Bayesian Updating MathCad Worksheet for Platform SS 269

This Worksheet Calculates the Posterior Distributions of Bias Factors

Table of Contents

1.0: Input of Structural Reliabiltiy Results

Bj = Bias factor for jacket strength
Bfl = Bias factor for foundation strength - Lateral
Bfa = Bias factor for foundation strength - Axial

Define Ranges of Bias Factors

$t := 12$

$$Bj := \left| \begin{array}{l} \text{for } i \in 0..t \\ \quad B_i \leftarrow .5 + (i+1)\cdot .1 \\ B \end{array} \right. \qquad Bfl := \left| \begin{array}{l} \text{for } i \in 0..t \\ \quad B_i \leftarrow .5 + (i+1)\cdot .1 \\ B \end{array} \right. \qquad Bfa := \left| \begin{array}{l} \text{for } i \in 0..t-2 \\ \quad B_i \leftarrow .9 + (i+1)\cdot .1 \\ B \end{array} \right.$$

Bj =

	0
0	0.6
1	0.7
2	0.8
3	0.9
4	1
5	1.1
6	1.2
7	1.3
8	1.4
9	1.5
10	1.6
11	1.7
12	1.8

Bfl =

	0
0	0.6
1	0.7
2	0.8
3	0.9
4	1
5	1.1
6	1.2
7	1.3
8	1.4
9	1.5
10	1.6
11	1.7
12	1.8

Bfa =

	0
0	1
1	1.1
2	1.2
3	1.3
4	1.4
5	1.5
6	1.6
7	1.7
8	1.8
9	1.9
10	2

The following table contains the failure probabilities calculated in STRUREL. These probabilities are the likelihood function for the Bayesian updating procedure.

$n := 1859$

$P2 :=$

1	bfl	bfa	Beta Low	Beta High	high jacket	low jacket	prob. Diff.	
0.6	0.6	1	-1.5513	-1.5513	9.396E-01	9.950E-01	5.539E-02	
0.6	0.6	1.1	-1.5513	-1.5513	9.396E-01	9.957E-01	5.613E-02	
0.6	0.6	1.2	-1.5513	-1.5513	9.396E-01	9.960E-01	5.644E-02	
0.6	0.6	1.3	-1.5513	-1.5513	9.396E-01	9.962E-01	5.658E-02	
0.6	0.6	1.4	-1.5513	-1.5513	9.396E-01	9.962E-01	5.664E-02	
0.6	0.6	1.5	-1.5513	-1.5513	9.396E-01	9.962E-01	5.666E-02	
0.6	0.6	1.6	-1.5513	-1.5513	9.396E-01	9.963E-01	5.667E-02	
0.6	0.6	1.7	-1.5513	-1.5513	9.396E-01	9.963E-01	5.668E-02	
0.6	0.6	1.8	-1.5513	-1.5513	9.396E-01	9.963E-01	5.668E-02	
0.6	0.6	1.9	-1.5513	-1.5513	9.396E-01	9.963E-01	5.668E-02	
0.6	0.6	2	-1.5513	-1.5513	9.396E-01	9.963E-01	5.668E-02	
0.6	0.7	1	-1.658	-1.658	9.513E-01	9.983E-01	4.694E-02	
0.6	0.7	1.1	-1.658	-1.658	9.513E-01	9.988E-01	4.742E-02	
0.6	0.7	1.2	-1.658	-1.658	9.513E-01	9.990E-01	4.761E-02	
0.6	0.7	1.3	-1.658	-1.658	9.513E-01	9.990E-01	4.769E-02	
0.6	0.7	1.4	-1.658	-1.658	9.513E-01	9.991E-01	4.773E-02	
0.6	0.7	1.5	-1.658	-1.658	9.513E-01	9.991E-01	4.774E-02	
0.6	0.7	1.6	-1.658	-1.658	9.513E-01	9.991E-01	4.775E-02	
0.6	0.7	1.7	-1.658	-1.658	9.513E-01	9.991E-01	4.775E-02	
0.6	0.7	1.8	-1.658	-1.658	9.513E-01	9.991E-01	4.776E-02	
0.6	0.7	1.9	-1.658	-1.658	9.513E-01	9.991E-01	4.776E-02	
0.6	0.7	2	-1.658	-1.658	9.513E-01	9.991E-01	4.776E-02	
0.6	0.8	1	-1.6831	-1.6831	9.538E-01	9.988E-01	4.497E-02	
0.6	0.8	1.1	-1.6831	-1.6831	9.538E-01	9.992E-01	4.539E-02	
0.6	0.8	1.2	-1.6831	-1.6831	9.538E-01	9.994E-01	4.555E-02	
0.6	0.8	1.3	-1.6831	-1.6831	9.538E-01	9.994E-01	4.562E-02	
0.6	0.8	1.4	-1.6831	-1.6831	9.538E-01	9.995E-01	4.565E-02	
0.6	0.8	1.5	-1.6831	-1.6831	9.538E-01	9.995E-01	4.566E-02	
0.6	0.8	1.6	-1.6831	-1.6831	9.538E-01	9.995E-01	4.567E-02	
0.6	0.8	1.7	-1.6831	-1.6831	9.538E-01	9.995E-01	4.567E-02	
0.6	0.8	1.8	-1.6831	-1.6831	9.538E-01	9.995E-01	4.567E-02	
0.6	0.8	1.9	-1.6831	-1.6831	9.538E-01	9.995E-01	4.567E-02	
0.6	0.8	2	-1.6831	-1.6831	9.538E-01	9.995E-01	4.567E-02	
0.6	0.9	1	-1.6478	-1.6478	9.503E-01	9.989E-01	4.859E-02	
0.6	0.9	1.1	-1.6883	-1.6883	9.543E-01	9.993E-01	4.497E-02	
0.6	0.9	1.2	-1.6883	-1.6883	9.543E-01	9.994E-01	4.512E-02	
0.6	0.9	1.3	-1.6883	-1.6883	9.543E-01	9.995E-01	4.519E-02	
0.6	0.9	1.4	-1.6883	-1.6883	9.543E-01	9.995E-01	4.522E-02	

1

2.0: Determine Marginal Posterior Distributions

The posterior distribution is the product of prior distribution and the likelihood function:

f"(bj,bfl,bfa) = f'(bj,bfl,bfa)*lk(bj,bfl,bfa)

```
Pp :=
  for  $i \in 1..n$
    $Pp_i \leftarrow \left(P2_{i,7}\right)\cdot\left(dnorm\left(P2_{i,0},1,.3\right)\cdot dnorm\left(P2_{i,1},1,.3\right)\cdot dnorm\left(P2_{i,2},1.3,.3\right)\right)$
  Pp
```

Note: Pp is the posterior distribution f"(bj,bfl,bfa)

The individual (marginal) posterior distribution is obtained by integrating out the other variables. Numerical integration is performed using the Trapozoidal Rule.

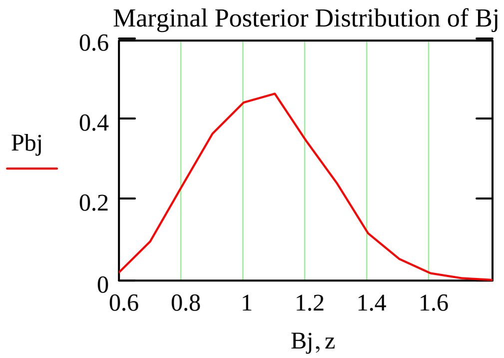
2.1 Determine Posterior Distribution of f"(bj)

For f"(bj), first integrate bfl out, and then bfa.

$k := 0 \quad s := 0 \quad d := 0 \quad ds := 0 \quad i := 0$

```
Pbbj :=
  for  $i \in 0..t$
    $Pb_i \leftarrow 0$
  for  $j \in 0..t$
    for  $k \in 0..t-2$
      for  $s \in 0..t$
        for  $i \in 0..n$
          if  $P2_{i,0} = Bj_j$
            if  $P2_{i,2} = Bfa_k$
              $Pb_s \leftarrow Pp_i$  if  $P2_{i,1} = Bfl_s$
              1
            1
          1
        $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
        $ps_{j,k} \leftarrow 0.05\cdot\left(Pb_0 + Pb_t + 2\cdot d\right)$
      1
  ps
```

```
Pbj :=
  for  $j \in 0..t$
    $ds \leftarrow \sum_{k=0}^{9} Pbbj_{j,k}$
    1
    $pss_j \leftarrow 0.05\cdot\left(Pbbj_{j,0} + Pbbj_{j,10} + 2\cdot ds\right)$
  pss
```

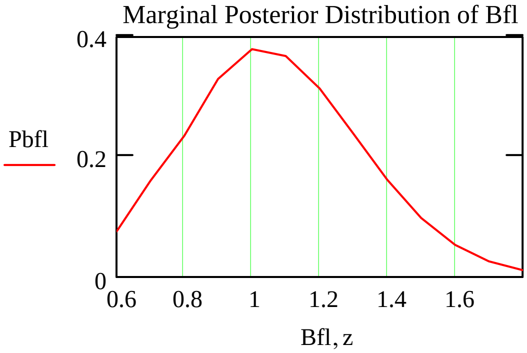


2.2 Determine Posterior Distribution of f"(bfl)

For f"(bfl), first integrate bj out, and then bfa

```
Pbbfl := for $i \in 0..t$
           $Pb_i \leftarrow 0$
         for $j \in 0..t$
           for $k \in 0..t-2$
             for $s \in 0..t$
               for $i \in 0..n$
                 if $P2_{i,1} = Bfl_j$
                   if $P2_{i,2} = Bfa_k$
                     $Pb_s \leftarrow Pp_i$ if $P2_{i,0} = Bj_s$
                     1
                   1
                 1
               $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
               $ps_{j,k} \leftarrow 0.05 \cdot (Pb_0 + Pb_t + 2 \cdot d)$
             1
         ps
```

```
Pbfl := for $j \in 0..t$
          $ds \leftarrow \sum_{k=0}^{9} Pbbfl_{j,k}$
          1
          $pss_j \leftarrow 0.05 \cdot (Pbbfl_{j,0} + Pbbfl_{j,10} + 2 \cdot ds)$
        pss
```

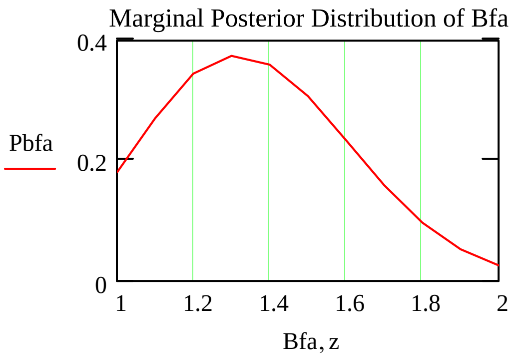


2.3 Determine Posterior Distribution of f"(bfa)

For f"(bfa), first integrate bj out, and then bfl.

```
Pbbfa :=  for $i \in 0..t$
            $Pb_i \leftarrow 0$
          for $j \in 0..t-2$
            for $k \in 0..t$
              for $s \in 0..t$
                for $i \in 0..n$
                  if $P2_{i,2} = Bfa_j$
                    if $P2_{i,1} = Bfl_k$
                      $Pb_s \leftarrow Pp_i$  if $P2_{i,0} = Bj_s$
                      1
                    1
                  1
                $d \leftarrow \sum_{h=1}^{t-1} Pb_h$
                $ps_{j,k} \leftarrow 0.05 \cdot (Pb_0 + Pb_t + 2 \cdot d)$
              1
          ps
```

```
Pbfa :=  for $j \in 0..t-2$
           $ds \leftarrow \sum_{k=0}^{11} Pbbfa_{j,k}$
           1
           $pss_j \leftarrow 0.05 \cdot (Pbbfa_{j,0} + Pbbfa_{j,12} + 2 \cdot ds)$
         pss
```



Note that the proper magnitude (scaling factor) of the above posterior distributions has not been determined yet. The magnitude of these distributions has to be normalized such that the areas of these curves are 1.0. This normalization will be performed as follows in which a log-normal distribution is fitted to each of these distributions.

3.0: Best Fit to Calculated Distributions and Determine Mean/Standard Deviations

Use the MathCad function "genfit" to find the best-fit log-normal distribution. The following three parameters will be identified:

g0 : Mean value of ln(z)
g1 : Standard deviation of ln(z)
g2 : A scaling factor to shift the log-normal distribution to fit the calculated posterior distribution

Function defined in the next expression is composed as follows:

1st element : Log-normal distribution
2nd element : Partial derivative of log-normal distribution w.r.t. g0
3rd element : Partial derivative of log-normal distribution w.r.t. g1
4th element : Partial derivative of log-normal distribution w.r.t. g2

$$\mathrm{Fl}(z,g) := \begin{bmatrix} \dfrac{g_2}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]} \\[2ex] \dfrac{g_2}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{z-g_0}{g_1}\right)^2\right]}\cdot\dfrac{\left(\ln(z)-g_0\right)}{\left(g_1\right)^2} \\[2ex] \dfrac{\dfrac{\left[e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}\right]\cdot\left(z-g_0\right)^2\cdot g_2}{\left(g_1\right)^2}\cdot\left[-e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]}\right]}{\left(g_1\right)^2\cdot z} \\[2ex] \dfrac{1}{g_1\cdot\sqrt{2\cdot\pi}\cdot z}\cdot e^{\left[\frac{-1}{2}\cdot\left(\frac{\ln(z)-g_0}{g_1}\right)^2\right]} \end{bmatrix}$$

3.1 Best fit of posterior distribution of bj

$$vgl := \begin{pmatrix} .09 \\ .22 \\ .45 \end{pmatrix}$$

Inital guess on g0, g1 and g2

$$Tl := \text{genfit}(Bj, Pbj, vgl, Fl)$$

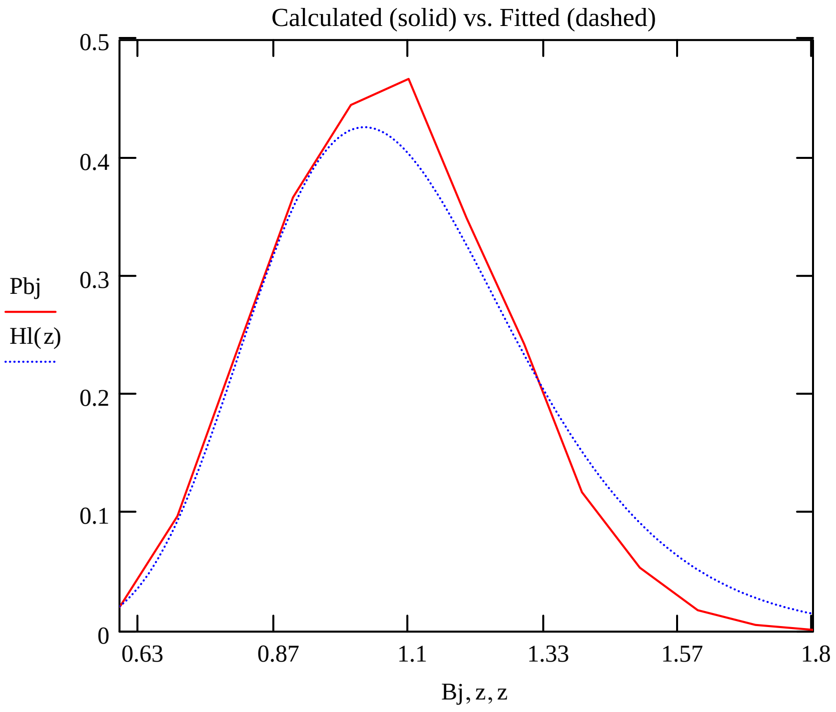
$$Tl = \begin{pmatrix} 0.071 \\ 0.218 \\ 0.244 \end{pmatrix}$$

Best fit solution

Calculate mean value and cov of fitted log-normal distribution

$$Hl(z) := Fl(z, Tl)_0 \quad hl(z) := \text{dlnorm}\left(z, Tl_0, Tl_1\right) \cdot Tl_2$$

$$mean := e^{\left[Tl_0 + \frac{(Tl_1)^2}{2}\right]} \qquad COV := Tl_1$$



Bj bias factor

$mean = 1.099$

$COV = 0.218$

3.2 Best Fit of Posterior Distribution bfl

$$vgl := \begin{pmatrix} 0.1 \\ .22 \\ 0.22 \end{pmatrix}$$

Initial guess on g0, g1 and g2

$$Tl := \text{genfit}(Bfl, Pbfl, vgl, Fl)$$

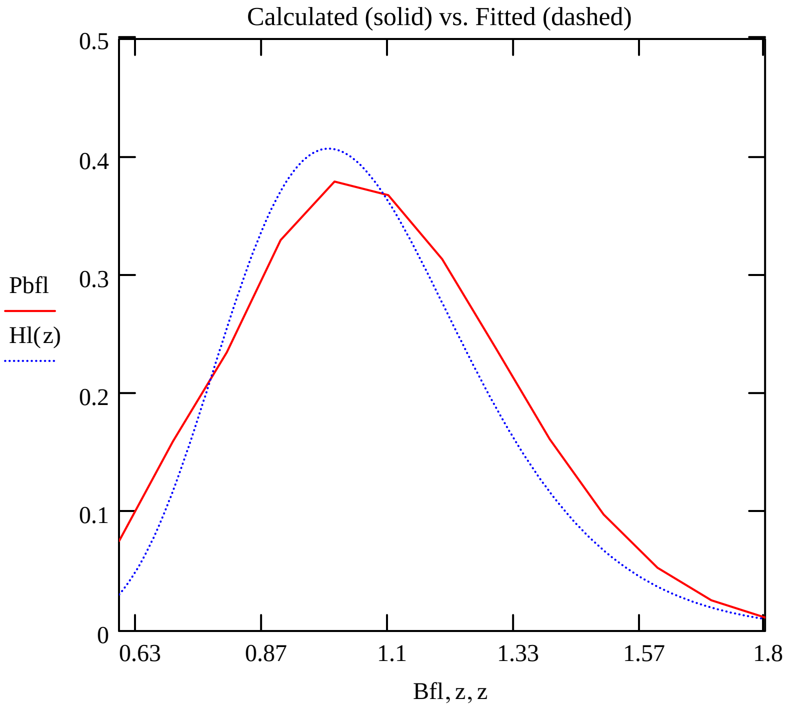
$$Tl = \begin{pmatrix} 0.038 \\ 0.22 \\ 0.228 \end{pmatrix}$$

Best fit solutions

Calculate mean value and cov of fitted log-normal distribution

$$Hl(z) := Fl(z, Tl)_0 \quad hl(z) := \text{dlnorm}\left(z, Tl_0, Tl_1\right) \cdot Tl_2$$

$$\text{mean} := e^{\left[Tl_0 + \frac{(Tl_1)^2}{2}\right]} \qquad COV := Tl_1$$



Bfl bias factor

mean = 1.064

COV = 0.22

3.3 Best fit on Posterior Distribution of bfa

$$\mathrm{vgl} := \begin{pmatrix} .35 \\ .2 \\ 0.3 \end{pmatrix}$$

Initial guess on g0, g1 and g2

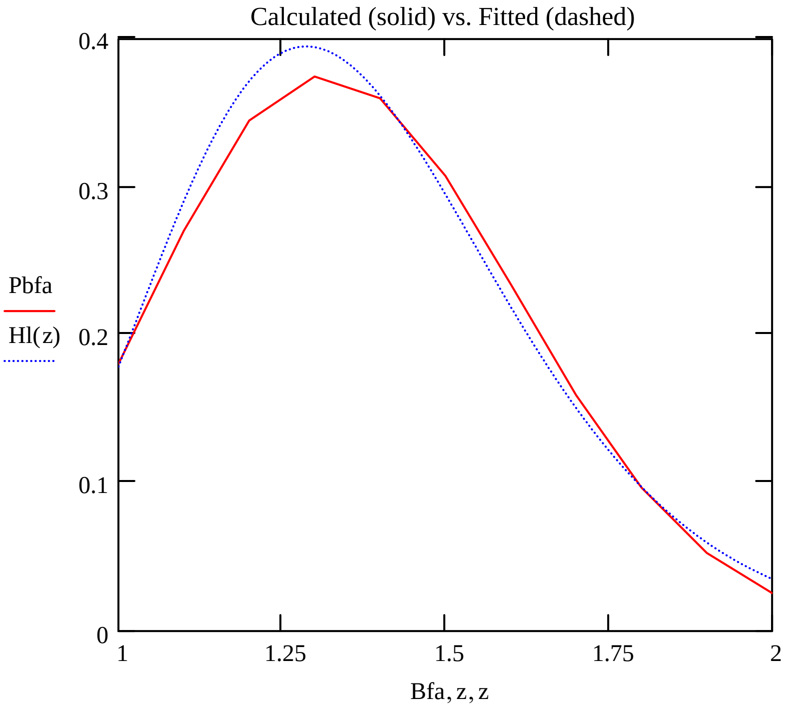
$$\mathrm{Tl} := \mathrm{genfit}(\mathrm{Bfa}, \mathrm{Pbfa}, \mathrm{vgl}, \mathrm{Fl})$$

$$\mathrm{Tl} = \begin{pmatrix} 0.293 \\ 0.2 \\ 0.261 \end{pmatrix}$$

Best fit solutions

$$\mathrm{Hl}(z) := \mathrm{Fl}(z, \mathrm{Tl})_0 \quad \mathrm{hl}(z) := \mathrm{dlnorm}\left(z, \mathrm{Tl}_0, \mathrm{Tl}_1\right) \cdot \mathrm{Tl}_2$$

$$\mathrm{mean} := e^{\left[\mathrm{Tl}_0 + \frac{\left(\mathrm{Tl}_1\right)^2}{2}\right]} \qquad \mathrm{COV} := \mathrm{Tl}_1$$



Bfa bias factor

mean = 1.367

COV = 0.2

4.0: Marginal Likelihood Functions

The likelihood function, lk(bj,bfl,bfa), has been used in previous sections in determining the posterior distributions of the bias factors. Note that lk(bj,bfl,bfa) is the structural reliability solution from STRUREL and is a function of all three bias factors, bj, bfl and bfa. lk(bj,bfl,bfa) is termed the "joint likelihood function".

For reference and comparison to the Andrew Phase 2 report, the "marginal likelihood function" is also calculated. The calculation of marginal likelihood function, for example lk(bj), is calculated by integrating the bias factors bfl and bfa out of lk(bj,bfl,bfa).

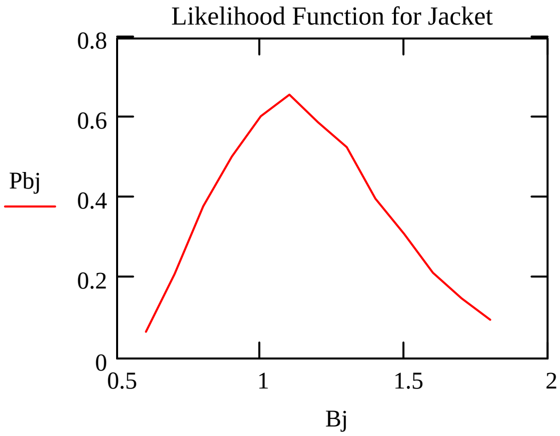
Note that the calculation in this section does not directly relate to the posterior distribution of the bias factors. These marginal likelihood functions are only calculated for reference purposes only.

4.1 Marginal Likelihood Function lk(bj)

```
Pbj := | for  i ∈ 0 .. t
       |   $Pb_i \leftarrow 0$
       | for  j ∈ 0 .. t
       |   for  i ∈ 1 .. n
       |     $Pb_j \leftarrow Pb_j + \left(P2_{i,7}\right)$  if  $P2_{i,0} = Bj_j$
       | $\frac{Pb}{100}$
```

Pbj =

	0
0	0.067
1	0.211
2	0.381
3	0.505
4	0.605
5	0.659
6	0.59
7	0.528
8	0.399
9	0.311
10	0.214
11	0.15
12	0.097

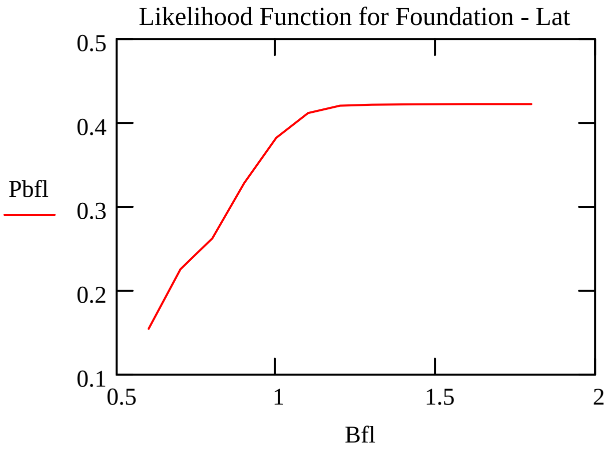


4.2 Marginal Likelihood Function lk(bfl)

```
Pbfl := | for  $i \in 0..t$
        |   $Pb_i \leftarrow 0$
        | for  $j \in 0..t$
        |   for  $i \in 1..n$
        |     $Pb_j \leftarrow Pb_j + \left(P2_{i,7}\right)$  if  $P2_{i,1} = Bfl_j$
        | Pb·.1·.1
```

Pbfl =

	0
0	0.155
1	0.226
2	0.262
3	0.328
4	0.382
5	0.412
6	0.42
7	0.422
8	0.422
9	0.422
10	0.422
11	0.422
12	0.422

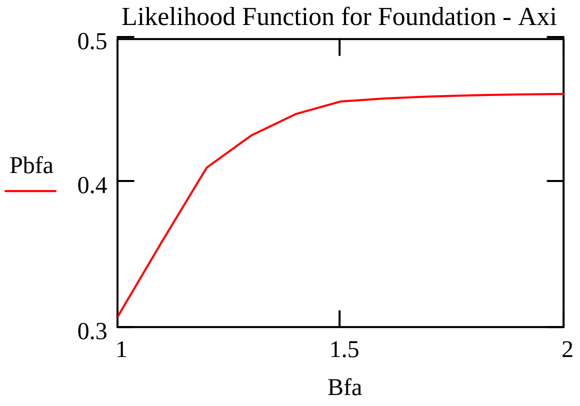


4.3 Marginal Likelihood Function lk(bfa)

```
Pbfa := | for  $i \in 0..t-2$
        |   $Pb_i \leftarrow 0$
        | for  $j \in 0..t-2$
        |   for  $i \in 1..n$
        |     $Pb_j \leftarrow Pb_j + \left(P2_{i,7}\right)$  if  $P2_{i,2} = Bfa_j$
        | Pb·.1·.1
```

Pbfa =

	0
0	0.307
1	0.36
2	0.411
3	0.433
4	0.448
5	0.457
6	0.459
7	0.46
8	0.461
9	0.461
10	0.462



Appendix B

OTC 16802

OTC 16802

Hurricane Lili's Impact on Fixed Platforms and Calibration of Platform Performance to API RP 2A

F. J. Puskar and A. P. Ku, Energo Engineering, Inc.; R. E. Sheppard, ABS Consulting, Inc.

This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, U.S.A., 3–6 May 2004.

Abstract

When Hurricane Lili passed through a region of offshore platforms in September 2003, it provided a new opportunity to “test’ the API RP 2A design process for fixed base platforms to ensure that it provides for well designed structures. While most platforms survived Lili, some were damaged and some failed. It takes all three of these results to adequately test a design code. The last similar opportunity was Hurricane Andrew in 1992. At that time, a Joint Industry Project (JIP) was initiated that developed such a testing process and demonstrated that API RP 2A was indeed functioning adequately, and results in a predictable platform design. The JIP was also used to assist in development of API RP 2A Section 17.

The first part of this paper describes the general impact of Hurricane Lili on offshore fixed platforms in terms of survival, damage and collapse of platforms. Specific findings and trends are reported related to global platform performance as well as component performance. The second part of the paper discusses an update to the Andrew JIP using results of several detailed platform assessments from Hurricane Lili. The approach uses a probabilistic “Bayesian” updating process to determine the adequacy of the API RP 2A platform structure design process, based upon “observed” platform failures and survivals during Lili. The result is a bias factor that reflects how well API RP 2A predicts platform behavior under extreme loads. The work was funded by the Minerals Management Service (MMS).

Background

In 1992, Hurricane Andrew damaged numerous offshore platforms in the Gulf of Mexico, causing several to collapse. This presented a unique opportunity to “test” the API RP 2A design process by comparing platforms that survived, were damaged, or failed in hurricane Andrew against what API RP 2A would have predicted. A Joint Industry Project (JIP) was initiated that developed and implemented a probabilistic comparison process based upon Bayesian updating. The process indicated that the API RP 2A design approach results in a conservative platform design with about 10 to 20 percent margin -- prior to the application of factors of safety. With the normal factors of safety included, the conservatism would be much higher. The Andrew JIP was funded by over 20 organizations including the MMS. There were two phases of the JIP as described in references 1 to 3.

Hurricane Andrew provided a unique opportunity for such a comparison process. However, one of the limiting factors was that only 13 platforms were used in the comparison process. Also, many of the platforms were in the same vicinity (South Timbalier), and of similar design (old Gulf Oil).

Also at that time, API was in the process of developing API RP 2A Section 17, which establishes a procedure for the assessment of existing platforms. The Andrew JIP was used by the API Section 17 Task Group to help test and calibrate the Section 17 process for assessment of existing platforms.

In 2002, Hurricane Lilly damaged several platforms, including a few that were a complete loss. This provided a similar opportunity as Hurricane Andrew had to further study the API process and update the Andrew comparison with new platforms – particularly those of different location and design.

Part I – Platform Performance in Hurricane Lili

General Storm Characteristics

Hurricane Lili began its track on September 21, 2002 as a tropical depression over the Atlantic Ocean. Lili moved across the Windward Islands as a developing tropical storm on the 23rd dumping heavy rains. The tropical storm weakened to a tropical wave on the 25th and 26th as it crossed the central Caribbean Sea. Lili regained tropical storm status on the 27th moving slowly around the north coast of Jamaica. Strengthening in the warm waters of the Caribbean, Lili hit western Cuba on October 1st as a Category 2 hurricane on the Saffir-Simpson scale. It moved into the Gulf of Mexico with winds of 145 mph as a Category 4 hurricane on the 2nd. Lili made landfall on the Louisiana coast on the 3rd as a borderline Category 1/Category 2 hurricane.

The hurricane path included a region of the Gulf that is densely populated with offshore platforms. As show in Figure 1, the center of the hurricane traversed the Green Canyon, Ship Shoal, Eugene Island, South Marsh Island and Vermilion areas. Approximately 800 platforms were exposed to significant wind and waves from Lili (5). Approximately 550 of these were exposed to the higher level Category 3 and 4 storm waves. As is typical in the Gulf of Mexico, the advance warning of hurricanes allowed some 25,000 workers to be evacuated from Gulf facilities prior to the storm reaching the area (5).

In some areas Lili's waves were nearly as large as those used for the design of new structures. The regions of platforms most significantly loaded by Lili, as defined by the Minerals Management Service (MMS), included the Eugene Island and Ship Shoal areas. Some of the platforms in these regions were older structures that were not originally designed to withstand the forces created by a hurricane of Lili's magnitude.

Platform Performance in Lili

Overall, the Gulf of Mexico platform fleet performed remarkably well – with most platforms surviving the storm with no major structural damage and able to return to operation as soon as staff returned to the facility.

Table 1 shows the 17 platforms that were identified by the MMS as sustaining significant damage from Lili (4). This information was gathered from reports sent to the MMS by platform owners. Only the region where the damaged platform was located is shown, with the specific platform name not identified due to confidentiality.

Several platforms sustained structural damage to horizontal and vertical members. A number of platforms were severely damaged ranging from failing deck members, failed jacket/pile connections, failed legs, buckled members, cracked joints and even mud-mat shifting. Hurricane Lili also resulted in the complete collapse of two platforms during the storm (EI 275 and EI 309). Some other key findings are:

- **Age.** As with prior hurricanes, age is the biggest factor in platform performance. Fourteen of the significantly damaged platforms were installed prior to 1980. Platforms in this era were designed when API RP 2A was still evolving and often had lower decks, smaller members and weaker joints than post-1980 platforms. These findings are consistent with those from Hurricane Andrew.
- **Wave-in Deck.** Several of the pre-1980 platforms were known to have low decks and likely failed due to the large forces exerted on a platform should a wave crest hit the deck structure.

For ten of the significantly damaged platforms, the damage was noticeable immediately following Lili. The MMS had required subsea inspections for platforms along the path of highest waves following Hurricane Andrew in 1992. The MMS also required this type of inspection following Lili, via a Notice to Lessees (NTL) No.: 2003-G04 issued in January of 2003. Such a Special Survey following an extreme event is also recommended in API RP 2A, Section 14.4.3 (7). The NTL required differing API Level surveys as follows:

- **Level I – above water visual** - all platforms exposed to wind speeds greater than 74 mph.
- **Level II – general underwater visual by divers or ROV** - all platforms located within 25 miles of Hurricane Lili's eye center storm track while it was a category III/IV (see Figure 1).
- **Level III – underwater visual inspection of areas of known or suspected damage** - all platforms that experienced wave loading in the deck and where Level II survey results prescribe Level III surveys.

The MMS also encouraged operators to first inspect the older platforms located nearest to the eye center storm track, and then gradually inspect those platforms towards the outer limits of the MMS defined area.

Following these underwater inspections, and additional seven platforms were identified with significant structural damage that had not been apparent. These platforms are shaded gray in Table 1. These findings validate the rational in API RP 2A and the MMS NTL of underwater inspections following extreme events.

Damaged Platform Case Studies

The following describes some of the "global" damage to several of the platforms identified in Table 1.

Eugene Island Platform – 4 Leg Leaning. This four-leg platform was installed in 1968 in approximately 110 feet of water. As shown in Figure 2, this uniquely configured structure uses conductors as two of its legs and conventional piled legs for the other two. The facility is not manned. Damage to this facility was apparent without underwater survey. There was gross deflection of all four legs including bulging noted in one leg above the water line. Visual indications, separated members and missing members were also noted from the post-storm underwater survey. Damage to the bridge connecting this platform to another facility was also noted. The operator determined that this facility would not be repaired or replaced.

Ship Shoal Platform – 8 Leg. This eight-leg platform was installed in 1965 in approximately 200 feet of water. This is a fairly typical eight-leg structure with single diagonal and k-brace vertical framing. The facility has permanent quarters and is bridge connected to another platform. Damage to this facility was not apparent prior to the post-storm underwater survey. The survey discovered several separated and missing members primarily between the levels just above the water line and the first horizontal framing level below the water line. The operator planned to repair the damage and continue to use the platform.

Eugene Island Platform – 4 Leg. This four-leg platform was installed in 1971 in approximately 170 feet of water. This is a fairly typical four-leg structure with single diagonal vertical framing. The facility has permanent quarters and is bridge connected to another platform. Damage to this facility was not apparent prior to the post-storm underwater survey. The survey discovered a damaged vertical diagonal running through the splash zone and a severely damaged leg. The operator has repaired the damage and is continuing to use the platform.

Eugene Island Platform – Complete Collapse Case. This platform was toppled by Hurricane Lili (Figures 3 and 4), even though it had passed the assessment process that was triggered by damage found in the platform in a underwater survey in 1997. The operator and the MMS knew the platform would not withstand storm forces much greater than that expected during a Sudden Hurricane event. Hurricane Lili imposed forces on the platform much greater than Sudden Hurricane forces and, as a result, the platform collapsed. Due to the assessment process, the operator was able to sustain production for an additional 5 years, taking the risk of higher removal cost should the platform be destroyed prior to production ceasing and normal removal operations being completed.

Eugene Island Platform – Survival Case. The operator of a Eugene Island platform standing in roughly 150 feet of water was considering expanding production capacity through the addition of new conductors and wells. The facility had originally been a typical eight-leg configuration that had been subsequently strengthened by the addition of two tripod structures arranged at both short ends. These tripods were attached to the original structure with above-water braces to provide additional capacity. The addition of new conductors to this system required a reassessment following the guidelines of API RP 2A, Section 17. The assessment showed that adding the new conductors would not be acceptable without additional strengthening of the system or reducing the loads. Rather than move the production to a new facility and leave the original platform as-is, the operator decided the best solution would be to install a new platform that could allow increased production for the field and at the same time provide additional strength to the existing structure so that it could withstand greater storm loads. This new four-leg platform would be connected to the existing facility both above the water line and at the mudline to improve load sharing between the two systems. Hurricane Lili passed very close to these two joined platforms. Based on hindcast information, the original structure, even with its strengthening tripods, would not be expected to withstand the loading. However, the combined system performed well and no significant damage was noted on either the old or the new platform.

Component Performance

In addition to the global performance of the platforms as demonstrated by these Case Histories, specific component damage was also of interest. Some examples are:

- **Braces.** Damage ranged from local buckling (Figure 5) to global buckling (Figure 6) to completely severed members (Figure 7).
- **Joints.** Damage at typical tubular joints included small to large cracks in welds, joint deformation, and complete brace pull-out from the chord. Large cracks were also located in several skirt pile connections on one platform.
- **Legs.** Several legs were damaged at brace joints where the brace damage had migrated into the leg, such as cracks. In one particular case, the leg severed, as shown in Figure 8, exposing the pile. Notice how the leg was flattened around the circumference, almost like an external ring stiffener, thought to be caused by the repeated pounding of the leg up-and-down due to wave action.
- **Appurtenances.** Damage was reported to many jacket appurtenances such as boat landings, barge bumpers, walkways, handrails and stairs. In one case the boat landing came off the platform (Figure 9) and fell onto several brace members below, further damaging the structure. However, in most cases this type of damage was not a significant structural concern.
- **Deck Structure.** The most serious damage was the bending of deck beams due to the large forces at the top of wave crests (Figure 10). Other damage included many instances of displaced deck grating (Figure 11).
- **Deck Equipment.** Waves and high winds caused damage to process and control equipment (Figure 12) as well as items not crucial to structural performance. This type of damage can be costly to repair and can cause delays in restarting the facility following a hurricane.

Part II: Calibration of Platform Performance to API RP 2A

Overall Approach

In order to properly calibrate a structural design process such as API RP 2A, it takes the actual field observations of structural “survivals” and “failures” during extreme events. These observations can then be compared to what would have been predicted- structure survival or failure - based upon an analytical prediction using a design code such as API RP 2A. The design code can then be calibrated depending upon how well it is, or is not, predicting these failures.

For a survival, the structure is tested under extreme loads and performs without damage or collapse. This is compared to the analytical prediction. This helps establish the lower limit on how well the analytical process works. If you only had survivals then the process would always appear to work well. Failures test the upper limit on how well the design process works. This helps establish the upper limits on how well the analytical process works. If you only had failures then the process would always appear to work poorly. When both survivals and failures (or severe damage) are observed, it provides an opportunity to find the boundaries of the process and determine the true performance of the design code.

Hurricane Andrew in 1992 provided the last good opportunity for this, and an elaborate JIP was put together to explore how well API RP 2A does in predicting platform performance in terms of survivals and failures (1, 2, 3). The shortcomings of that work were that it represented results from only a single extreme event – Hurricane Andrew, and that many of the failed platforms were of similar vintage and design (old Gulf Oil). Therefore, when Hurricane Lili caused similar (but not as severe) damage to the offshore fleet as Andrew, it provided a good opportunity to combine the results of both storms for a single calibration of API RP 2A.

Calibration Methodology

A complex probabilistic, Bayesian updating methodology was introduced in the previous Andrew study for the calibration, and is explained in detail in that reference (3). This study follows a similar methodology, which will only be summarized here.

The method works by introducing a "Bias Factor" that is used to "correct" the *API RP 2A computed performance* of the platform compared to the *observed performance*. In this case, *performance* is defined as the safety factor, defined as the traditional ratio of resistance (R) to load (S):

$$\left[\frac{R}{S}\right]_{observed} = B \cdot \left[\frac{R}{S}\right]_{computed}$$

Determination of the bias factor gives an indication of the accuracy of the computed platform safety factor. A value of $B<1$ indicates that the computed platform safety factor is unconservative, and a value of $B>1$ indicates that the computed platform safety factor is conservative.

The computed [R/S] is determined using API RP 2A formulations to determine platform resistance (R) and platform load (S). The resistance is computed as the global platform lateral resistance (in terms of kips of base shear) as determined using a nonlinear pushover analysis, as described in API RP 2A Section 17 (7). In this case all of the normal material and design process factors of safety have been removed – so that this value is an ultimate strength value and represents the lateral load at which the platform would collapse. The load is computed as the global load (in terms of kips of base shear) that is acting on the platform during the storm (e.g., Andrew or Lili), computed according to the API RP 2A 21st Edition wave load recipe.

The observed [R/S] is the actual performance of the platform during the storm, and is set to less than one if the platform fails and greater than one if the platform survives.

Andrew vs. Lili Calibration Process

The Andrew JIP was conducted over ten years ago and the organization that performed the work and the computer codes and input used for the Bayesian updating process were no longer available. Therefore, the software program and input for the reliability process for this work were somewhat different, although both the Andrew and this work used FORM and SORM probabilistic methods for the analysis.

Because of this, the first step was to redo all of the Andrew calibration work, and benchmark it to the Andrew JIP results. For this effort, the later Andrew JIP II work (2) was the starting point. The benchmarking exercise indicated that the calibration process matched that used for Andrew.

Determination of Platform Performance

The Andrew Phase I JIP developed a global bias factor for the overall Jacket/Foundation system. The Andrew Phase II JIP developed bias factors for the Jacket *and* Foundation, with the Foundation further split into Lateral and Axial Capacity. Three failure modes and corresponding bias factors were therefore investigated in this study, per below, which follows the Andrew Phase II approach.

- Jacket Capacity Bias (Bj) – Failure or damage of the jacket above the foundation (i.e., failure at a joint or leg).
- Foundation Lateral Capacity Bias (Bfl) – Failure or damage of the pile in a lateral direction (i.e., yielding of the pile section).
- Foundation Axial Capacity (Bfa) – Failure or damage of the pile in the axial direction (i.e., plunging or pullout of the pile).

However, specific observations of the above are not always apparent (especially the foundation) and it is not always known what may have been the cause of collapse. Therefore, the observed platform performance was grouped into different categories based on the following calibration conditions.

- Survival – No damage, or only minor non-structural damage identified.
- Damage, Type I – Known damage to the jacket, foundation assumed intact.
- Damage, Type II – Known damage, but not attributed specifically to jacket or foundation.
- Failure, Type I – Known failure of the jacket, foundation assumed intact.
- Failure Type II – Known failure, but not attributed specifically to jacket or foundation.

Results - Bias Factors

A total of five Lili platforms will be used in the calibration process. At the time of this printing, results were available for only three of the platforms. These platforms are listed in Table 2 including the Platform Performance (Survival, Damage I) and the Jacket/Foundation Bias Factors. The Mean is the central value of the resulting probability distribution. As noted previously a value greater than 1.0 indicates that the API RP 2A process is conservative. For example, for SS 269 the Jacket Bias Factor Mean is 1.08. In other words, for this specific platform, the API RP 2A design process overestimates the ratio of [R/S] by about 8 percent. The COV is the Coefficient of Variation of the distribution, with a higher value meaning more variation. The typical values of 0.2 to 0.3 represent a reasonable confidence in the results.

It is noted that all of the bias factors exceed unity, even for the results from damaged platforms. This is because in these damaged platforms, the predicted maximum load is close or exceeds the collapse load. However, only damaged members (not collapse) were observed for these platforms. The fact that all of the bias factors exceed unity indicates that the API RP 2A process is conservative. In other words, it has predicted more damage and failure than was actually observed. The results should be considered as evidence supporting the use of the API process developed by industry in that they appear to be conservative overall. It is not recommended that the calculated bias factors be applied to individual platforms in any assessment since they were derived from a small sample of platforms. Also, the individual platform bias factors ranged from 1.08 to 1.16 for jacket structure capacity, from 1.08 to 1.10 for foundation lateral capacity, and from 1.36 to 1.37 for foundation axial capacity indicating that the application of a single average bias factor on an individual platform may not be appropriate.

The Bias factors of the individual Lili platforms shown in Table 2, were combined to develop a single set of Bias factors as shown in Table 3. Also shown are the Hurricane Andrew Bias factors (nine platforms involved) from the Andrew JIP Phase II results, as well as the Lili and Andrew Bias factors combined. Figure 13 shows a graphical representation of the distributions. Results are generally similar for both Andrew and Lili – with an overall observation that API RP 2A does an excellent, somewhat conservative, job of determining platform performance.

The Lili jacket bias factor is higher than the Andrew results. This can be attributed to one damaged platform (EI 231), in which the calculation shows the maximum base shear already exceeds the jacket collapse strength. In reality, this platform is left standing with only several damaged members.

The foundation lateral strength bias factor for Lili is smaller than the Andrew results (mean value of 1.12 versus 1.28). This can be attributed to the fact that no good evidence of foundation damage was observed after Hurricane Lili, thus no significant information was fed into the Bayesian updating procedure. This creates a minor change after the Bayesian updating when compared to the prior distribution (mean value of 1.0). The combined bias factor for foundation lateral strength is close to the Andrew results, further indicating that the weighting on the Lili information is minor.

The Hurricane Lili work shown here involves three platforms (one survival platform, two damaged platforms), thus representing a smaller sample size compared to Andrew calculation. Later work will expand the set by adding two more damaged platforms for a total of five platforms for Lili.

Conclusions

Hurricane Lili provided a unique opportunity to study the structural performance of offshore platforms under extreme metocean loading conditions. Hurricane Andrew was the last such opportunity in the Gulf of Mexico.

Overall Platform performance was as expected – with older pre-1980 platforms sustaining most of the significant damage. Several of the platforms failed due to wave-in-deck loading as has been previously observed in Hurricane Andrew. Several platforms had been through a Section 17 assessment, and had performed as API had predicted - in one case the platform collapsed, in another case the platform survived (after strengthening).

The calibration indicated similar results as the Andrew JIP – that API RP 2A does an excellent, somewhat conservative, job of predicting platform performance. The results of Lili combined with Andrew indicated that API RP2A provides an overall conservatism of 10-20% for platform design, even after all factors of safety have been accounted for.

Acknowledgements

The authors wish to thank their respective companies for the opportunity to publish this paper. We also wish to thank the MMS for sponsoring this effort.

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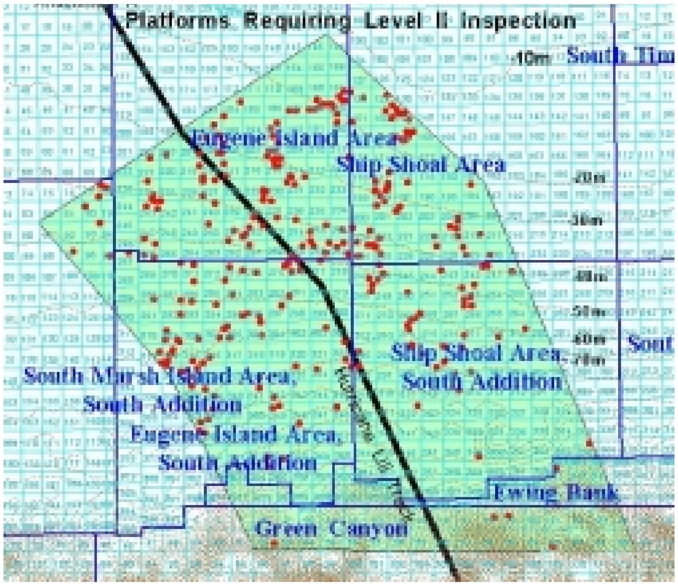

Figure 1 – Path of Lili through Offshore Fields. Shaded area indicates regions of post Lili underwater inspections per MMS NTL 2003-G04. Dots indicate platforms.

Figure 3– Eugene Island Platform Prior to Lili

Figure 2 – Leaning Platform

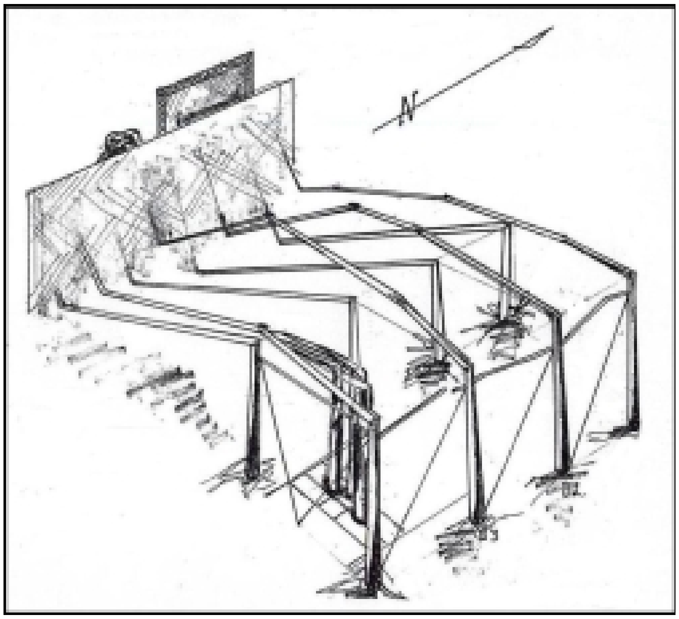

Figure 4 - Eugene Island Platform After Lili. Sketch based upon diver, ROV and sonar data.

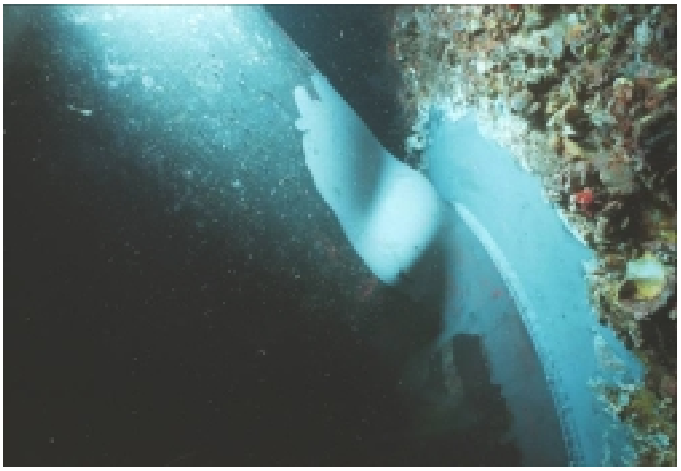

Figure 5 – Local Buckle of a Brace near a Joint

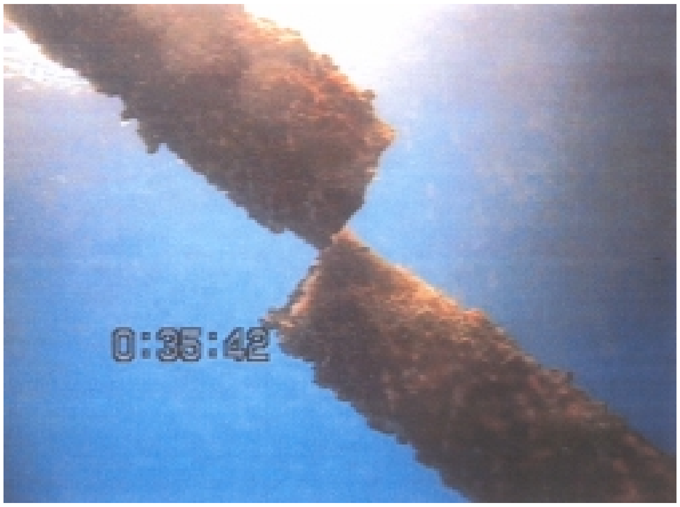

Figure 7 – Severed Brace

Figure 6– Global Buckle of Brace. Picture taken during removal.

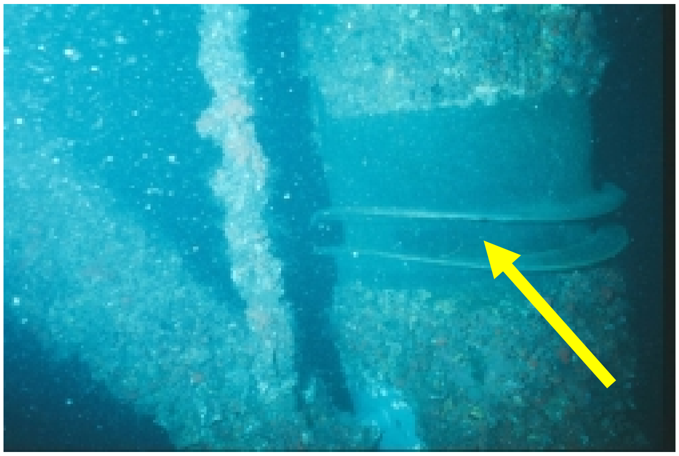

Figure 8 – Severed Leg. Arrow shows exposed pile.

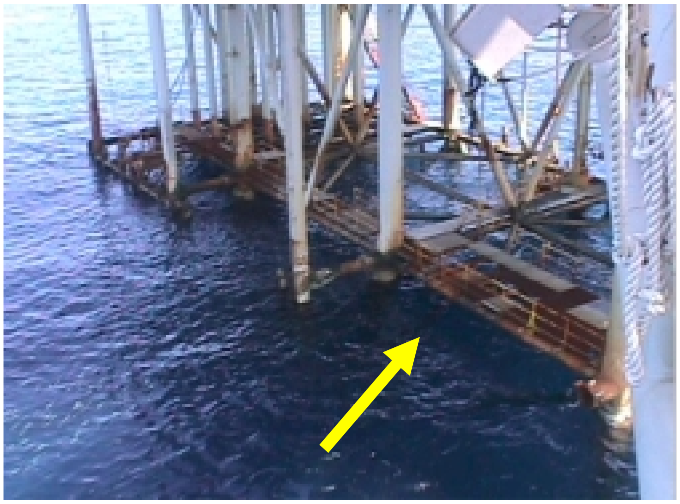

Figure 9 – Missing Boat Landing

Figure 10 – Bent Beams Under Deck

Figure 11 – Displaced Grating from Wave-in-Deck Forces

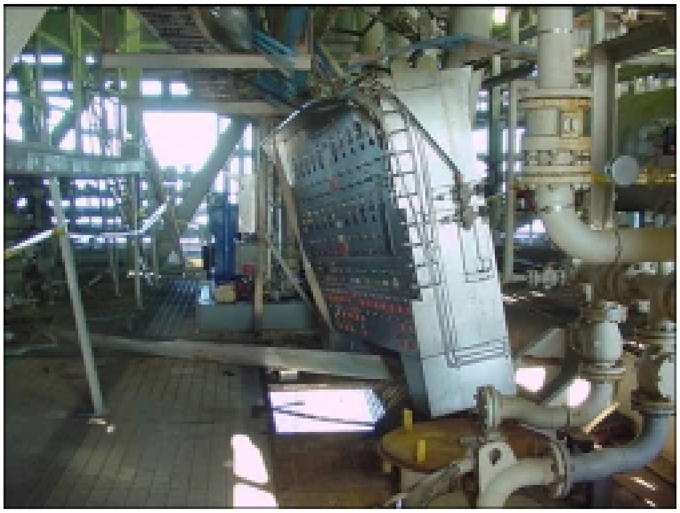

Figure 12 – Damaged Equipment from Wave-in-Deck Forces

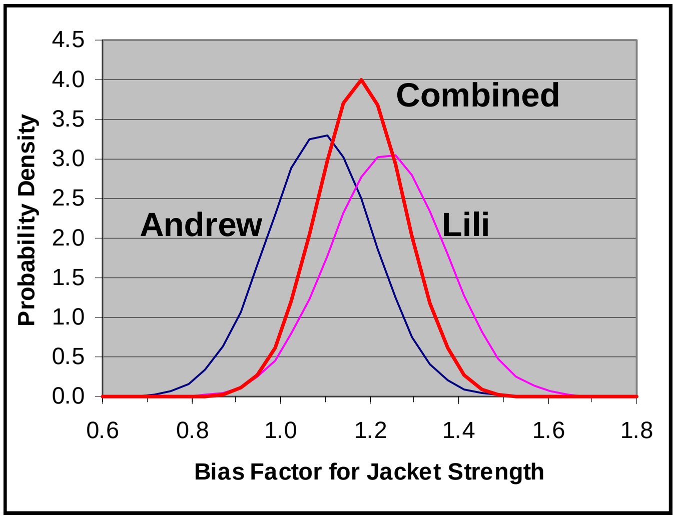

Figure 13 – Bias Curves for Andrew, Lili and Combined

Area	Block	Description of Platform and Damage
EI	176	Installed in 1958 in 80 feet of water. Damage to skirt pile framing (cracks) necessitated the removal of this platform. This damage could only be detected by underwater survey.
EI	215	Installed in 1983 in 98 feet of water. Damage includes a visible lateral deformation and the platform was being removed.
EI	231a	Installed in 1968 in 111 feet of water. Damage includes a visible lateral deformation and the platform will be removed.
EI	231b	Installed in 1971 in 106 feet of water. Heavy damage was visible without underwater survey.
EI	273	Installed in 1970 in 191 feet of water. Underwater survey post-Lili identified four damaged k-nodes in the transverse framing rows. Also impact damage to a vertical diagonal was identified. Clamp repairs are planned for this structure.
EI	275	Installed in 1964 in 172 feet of water. This platform was destroyed (toppled) by Hurricane Lili.
EI	276	Installed in 1971 in 172 feet of water. Post-Lili underwater survey identified damage to a vertical diagonal through the splash zone and leg severance near El. (-) 22'. This damage was repaired by member replacement and leg grouting.
EI	295	Installed in 1972 in 211 feet of water. Evidence indicates a wave crest 5 feet above the cellar deck during Hurricane Lili. Damage to the jacket includes a severed leg, damaged k-node and three damaged vertical diagonals all in the same vertical row near El. (-) 33'. This platform has been abandoned.
EI	309	Installed in 1969 in 218 feet of water. This platform was destroyed by Hurricane Lili.
EI	314	Installed in 1973 in 235 feet of water. A boat landing became detached during the storm and its fall collapsed some vertical diagonal braces. This damage could only be detected by underwater survey.
EI	322	Installed in 1978 in 235 feet of water. A fabrication flaw led to the failure of a leg/pile connection weld. This led to severe damage to the platform which was stabilized, decommissioned and removed.
EI	324	Installed in 1990 in 260 feet of water. MMS indicates that the platform damage was severe enough to require removal.
EI	330a	Installed in 1971 in 244 feet of water. Post-Lili underwater survey identified heavy damage.
EI	330b	Installed in 1971 in 248 feet of water. Post-Lili underwater survey identified heavy damage.
EI	337	Installed in 1982 in 268 feet of water. Post-Lili underwater survey identified heavy damage.
SS	204	Installed in 1968 in 100 feet of water. Post-Lili underwater survey identified crack indications in conductor guide framing members at the (-) 25' elevation.
SS	269	Installed in 1965 in 170 feet of water. Post-Lili survey identified 8 broken or missing vertical diagonal members through the splash zone.

Table 1 – Platforms with Significant Damage from Hurricane Lili. Gray shading indicates that the platform damage was found via underwater inspection.

			Mean	COV
SS 269	Damage I	Bj	1.08	0.20
		Bfl	1.10	0.22
		Bfa	1.37	0.20
EI 231	Damage I	Bj	1.16	0.22
		Bfl	1.08	0.25
		Bfa	1.36	0.22
EI 225	Survival	Bj	1.09	0.20
		Bfl	1.07	0.22
		Bfa	1.37	0.19

Table 2 – Bias Factor Mean and COV for Lili for Three Platforms

	Andrew		**Lili**		**Combined**	
Bias Factor	**Mean**	**c.o.v.**	**Mean**	**c.o.v.**	**Mean**	**c.o.v.**
Jacket	1.09	0.12	1.24	0.13	1.18	0.10
Foundation Lateral	1.28	0.17	1.12	0.22	1.31	0.17
Foundation Axial	1.35	0.20	1.37	0.19	1.32	0.18

Table 3 – Calculated Strength Bias Factors from Hurricane Andrew, Lili and Combined

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