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Reengineering history: What can we learn from a photographed B-17 "Flying Fortress" in-flight structural failure?

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Historical research is defined as the process of critical inquiry into past events to produce an accurate description and interpretation of those events. While using different information sources an attempt is made to reconstruct what happened during a certain period of time as completely and accurately as possible. The purpose of historical research is to make people aware of what has happened in the past in order to, for example, to learn from past failures and successes and apply them to present-day problems. Historical research is similar to Forensic Engineering which tries with the application of engineering principles to investigate failures with the goal to understand and prevent future events. An interesting example is the B-17 "Flying Fortress" bomber. Despite setbacks and crashes of the prototypes, it eventually became the iconic bomber of World War II. Nearly 13,000 bombers were built and a few of them are still flying today. During its operational service above the European theater in World War II the B-17 was hit and damaged many times. In some cases, an aircraft could return to its home base, in other instances, the damage was too great and the aircraft crashed and was destroyed. The focus of this paper is an accident which happened on May 19^{th} 1944, when the left horizontal stabilizer of a B-17 was hit by a bomb dropped from another B-17 flying in formation above. This event was captured by a camera located behind bomb bay which show the sequence of events in several photographs. Historical background information about the B-17 will be used to understand how it was designed with emphasis on the horizontal stabilizer. Using a forensic engineering perspective, this information will be used to understand and attempt to explain what happened. The B-17 stabilizer bomb impact event is part of an ongoing research project.

I. Nomenclature

A_{br}	=	projected bearing area
A_t	=	net-section area lug
a_g	=	gravitational acceleration 9.81 m/s^2
$c.g.$	=	aircraft center of gravity
d	=	base distance lug element
D	=	lug-hole diameter
E	=	energy
F_{impact}	=	impact force
F_{tru}	=	transverse ultimate strength
$F_{stabilizer}$	=	stabilizer force
F_u	=	axial ultimate strength
F_x	=	force X-direction
F_y	=	force Y-direction
F_z	=	force Z-direction
h	=	drop height/distance
K_{tru}	=	efficiency factor for transverse load
K_t	=	efficiency factor for axial load
K_{br}	=	efficiency factor for shear bearing
K_{bp}	=	plastic bending coefficient
m_{bomb}	=	mass bomb
mac	=	mean aerodynamic chord
N	=	Newton
P_u	=	axial ultimate load lug
P_{tru}	=	transverse ultimate load lug
P_θ	=	oblique ultimate load lug
R_a	=	load ratio axial load ($\theta = 0$)
R_{tr}	=	load ratio transverse load ($\theta = +/-90$)
R_θ	=	resultant lug load
t	=	thickness lug element
w	=	width lug element
W	=	work
$W_{c.g.}$	=	weight at aircraft c.g.
δ	=	impact distance
θ	=	angular location around lug hole
σ	=	normal stress
τ	=	shear stress

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II. The B-17 Development

On August 8th 1934, the United States Army Air Corps (USAAC) put out a tender requesting the development of a 250-mph bomber with a desired range of 2000 miles and an operating ceiling of 10,000 feet [1, 2]. The USAAC was looking to replace the Martin B-10 all-metal monoplane bomber, for this tender Boeing proposed Model 299. A reporter for the Seattle Times, coined the name "Flying Fortress" upon his witnessing the initial roll out exposing multiple machine gun installations. Since that time the name "Flying Fortress" stuck and is synonym for the B-17.

On October 30th, 1935, during evaluation exercises for the USAAC, the 299 crashed shortly after take-off (Fig. 1). The gust locks were left engaged and this oversight resulted in the aircraft entering a steep climb and stall immediately after take-off. The official investigation into the cause of the crash was concluded in December as pilot error and the Model 299 was absolved of having any defect contributing to the crash [3].

The US Army Air Corps disqualified the Boeing 299 following the crash and the twin-engine Douglas DB1 won the tender bid. However, a small number of 299s were ordered for evaluation as the performance at the time was excellent and better than the DB1. The service test order for thirteen model 299s would be the birth of a historical aircraft.

Fig. 1 Side view Model 299 after the crash during evaluation exercise [4].

III. The Design

Boeing designers C.N. Monteith, Robert Minshall, E.G. Emery and Ed Wells led to the design effort. They interpreted the USAAC request for a multi-engine bomber to be one with four engines rather than the standard two-engine design [5]. The proposal called for a flying prototype before August 1935 required to reach a speed of 200 mph and range of at least 1,020 miles. In addition to the B-17 flying and fighting characteristics the design was aimed to permit the manufacturing in large quantities, provide for interchangeability of parts, service and repair under adverse wartime conditions, and be sufficiently conservative in design to allow for modification in keeping with the ever-changing conditions of war [6].

At the first meeting of the Board of Directors of the newly independent Boeing Airplane Company, a sum of

$275,000 was voted to design and construct a four-engine bomber, Model 299. Engineering went on an overtime basis—the whole plant was organized on a one-job, maximum-effort basis [1]. This resulted in a patent being filed on Robert J. Minshall and assigned to the Boeing Aircraft Company [7]. By early July 1935 the prototype was constructed and ready to fly from Boeing Field. The B-17's wingspan was 103 feet and 9.38 inches with an area of 1,420 sq. ft. The fuselage was made out of an all-metal, semi-monocoque structure housing the 10 men crew at different positions. In the forward section ahead of the bomb bay the flight deck and nose gunner section is located. The bomb bay is located between the wings near the aircraft c.g. and has 4 bomb racks. The number and weight of bombs vary from 100lb up to 2000 lb some of which are carried outside the fuselage [8]. Behind the bomb bay in the tail section was the radio room with side window gunner positions. In the radio room a camera pit was installed for taking photographs for post mission analyses. The belly turret gun is also located under the tail section and in the far aft the tail gunner was located.

The B-17 horizontal stabilizer Fig. 2 has an area of 250.6 sq. ft. and is set at 0° relative to longitudinal axis. The front spar extends 19.167 feet to within 8 feet of tip end. The longer rear spar extends to the tip joining point. From the point where the front spar stops to the end of the tip, the leading edge and rear spar take over as the torsion-carrying structure. The two I-type spar beams have hydro-pressed webs with at the end a steel male attachment fitting. These end fittings can be joined with a steel taper pin onto bulkhead section 8 and 9 of the rear fuselage which has a female type fitting. The stabilizer has a NACA 0012 symmetrical profile which allows the stabilizer to be interchangeable on the left and right hand side. The flying characteristics of the B-17 were good as it was designed as a bomber flying long missions. The B-17 was not designed for spins and steep dives care must be taken to recover the aircraft [8]. A limit load factor of 3 is given for a design gross weight of 48,726 pounds [9].

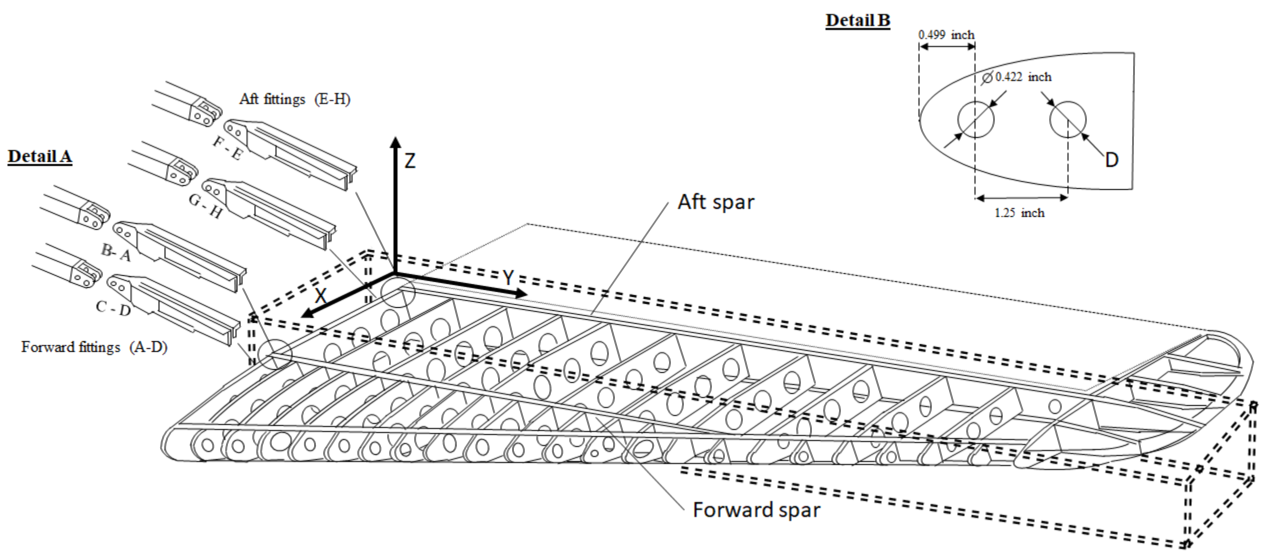


Fig. 2 Horizontal stabilizer assembly B-17 with fittings (Detail A) and lug measurements (Detail B).

One major design change of the B-17 stands out which was brought about by another unfortunate accident. In September 1934 a study was done for a civilian airliner version of the B-17. The aircraft designated as Model 307 was primarily based on the B-17C (Model 299H). The difference between the Model 307 Stratoliner and the B-17C was the fuselage design, the 307 would have a pressurized cabin. On march 1938 the Model 307 experienced a test flight accident during a stall recovery [10]. Following this accident wind tunnel tests were done to determine shortcomings of the 307. After analysis of the flight test and wind-tunnel data, several modifications were made including improved lateral stability by a adding a dorsal extension to the tail. The dorsal fin extension was a major change that was also implemented on the B-17D and subsequent models [11].

During World War II, the B-17 design evolved with an increase in armament and numerous engineering changes. Few changes were introduced to improve manufacturability or otherwise address concerns and suggestions from the shop floor. Boeing's engineering department was overwhelmed by battlefield requests that uncovered potential weaknesses. Most changes led to an increase in B-17 armament, which resulted in increasing assembly complexity [12]. In history, numerous examples have been documented of the B-17 surviving large holes and flack damage with the capability of returning home. Consequently, flight crews liked the B-17 because of its reputation as the flying fortress.

IV. The production

In 1936, the United States federal government ordered 13 B-17s and a new plant, Plant №2 was built for this purpose by Boeing with the utmost flexibility in mind. In practice, work in progress moved from the west end of the building, where machine shops were located, toward final assembly at the east end just off the airfield. During the war the factory roof was painted to resemble the town across the river and hide the factory from being a potential target for the Japanese.

Early in 1941 President Roosevelt ordered the Air Corps to initiate a program looking at producing 500 heavy bombers a month. After numerous conferences with the leading aircraft and accessory firms, they decided that a joint production project would be absolutely necessary if they were to meet the goal demanded by the President. No individual manufacturer could hope to achieve this level of output singlehandedly. Three manufacturers (Boeing, Douglas and Vega) were asked to manufacture the B-17 during World War II [13–15]. The design, materials, standards and quantities were fixed however the production method was left to the individual manufacturer. Each manufacturer had a different approach for building an aircraft. The Boeing "multiline" system is based on jig assembly of large sections which are completely equipped with installations before being joined with other sections. The Douglas method starts with sections in jigs, after being tied together, they are attached to carriers for a steadily progressing trip through numerous stations of an assembly. The Vega method is described as "a pre-assembled, skinned section break down system". Here assembled skinned panels of the exterior sections and interior structural components are being assembled with as many installations as possible before being joined to other components.

The B-17 was a complex airplane to build, requiring tolerances as tight as 0.005 inches and more than six miles of wiring. The five airplanes delivered in September 1941 consumed on average 142,837 direct labor hours per airframe: the equivalent of approximately 71 worker-years [12]. Thereafter, unit direct labor hours followed a declining trend. They bottomed out in August 1944 at 15,316 hours, almost one-tenth of what had been needed 35 months earlier.

Boeing's production method featured a combination of stationary subassembly and short multi-line final assembly. The idea was to minimize the time work in progress spent in the final assembly stage, because once the fuselage and the wings were joined, the airframe wasted space on the shop floor and unnecessarily increased the time workers spent walking back and forth. Thus, Boeing chose to break down the B-17's airframe production into roughly fifty sub-assemblies. These sub-assemblies were neatly jammed into sections of their own in the subassembly area and completed there as independent units by moving crews while stationary in a holding jig. This special production method devised by Boeing is referred to as multi line production. During World War II, the B-17 production was in full swing and reached a top peak 362 units per month in March 1944. A total of 12,731 B-17's were built by the end of the war of which 3,000 by Douglas and 2750 by Vega, the rest were produced by The Boeing aircraft company.

V. Formation flying

The original objective for bomber flying in formation was to concentrate sufficient fire power to permit the formation to fly anywhere in spite of enemy fighter attacks [16]. At the start of the war the B-17 would fly in a "V" or "Javelin" formation. These initial formation were flexible but could only bring a small number of guns to attack enemy aircraft. At the time no long range fighter aircraft were available to escort the B-17s on their full mission. With the development of long-range fighters as the Lockheed P-38 Lightning and Republic P-47 Thunderbolt and later the North American P-51 Mustang the bomber formations changed to make use of fighter escort. The 305^{th} bomber group had a reputation for tactical innovations which was due to LeMay who instigated rigorous training and tactics. LeMay experimented with tactical formation flying and developed a staggered three-element combat box formation with eighteen bombers 3. The three six aircraft squadrons were positioned in a compact high-lead-low wedge shape formation. Under LeMay guidance the bomber group was tasked to follow the leader and drop on his command. Having the lead specially trained and equipped with guidance capability and directional radar (path finder) resulted in a well concentrated grouping of bombs on target.

In January 1944 the box formation was adopted as general practice and was used for missions. The box formation was tuned to best use the B-17 armament and defend the formation. The formation also needed to be close together to give a better bomb pattern and minimize the time over heavy flak defenses and anti-aircraft guns which could only fire on a few number of the units at the time. The three squadrons element flew in a box of 160 feet wide by 150 feet high, the distance was close and staying in formation was essential Fig 3.

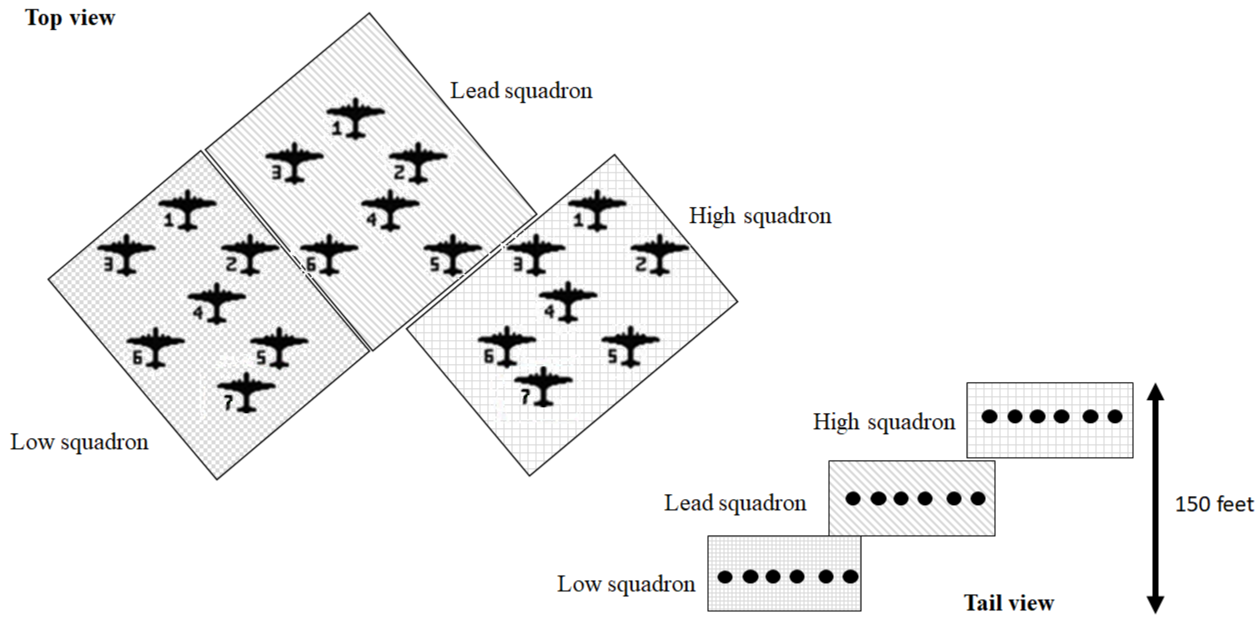


Fig. 3 "Box formation" flown by the B-17s with aircraft position numbers.

VI. The event

This section will describe the event of a bomb hitting the left horizontal stabilizer in flight while bombing. It is based on historical records, photographs and witness reports. It is divided into three paragraphs related to the mission, the missing air crew report and witnesses.

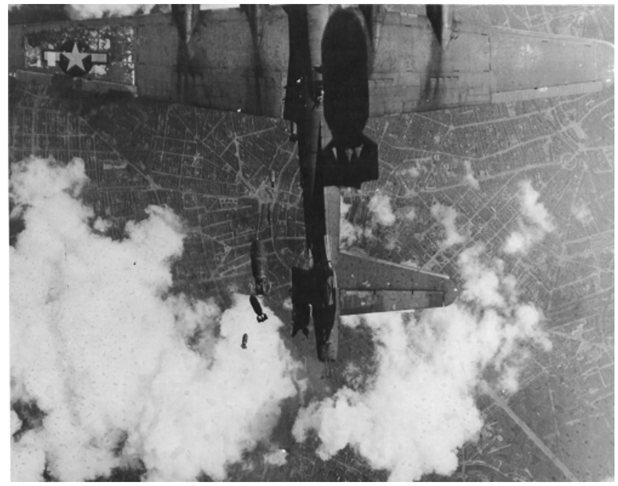
A. The mission

On May 19^{th} 1944 the 94^{th} bomber squadron was getting ready for Mission 358/131, with the target the German city of Berlin. A total of 20 aircraft were scheduled for the mission. The flight time would be 9 hours long via the North Sea and Denmark heading to Berlin from the north. Each aircraft carried a total bomb load of five 1000lb. bombs and had a fighter escort along the way. A box formation was flown for defensive purposes Fig. 3. The mission went according to plan and above Berlin at around 13:55 the bombs were released. During the bomb release photographs were taken from the camera pit. The photographs show that during the release of the bombs a lower B-17 left horizontal stabilizer was hit. Figure 4 shows the sequence of events. According to records, the lower B-17 was "Miss Donna Mae II" (42-31540) of the 331^{st} Bomb squadron/94BG piloted by Lt. M.U. Reid. The top aircraft was the B-17F "Trudy" (42-97791) of the 332^{nd} Bomber Squadron piloted by Lt. J. Winslett. According to records aircraft number 42-31540 was a B-17G-20BO which was built by Boeing and delivered in 1942 as Air Force Serial 6564. No maintenance records could be obtained for this aircraft.

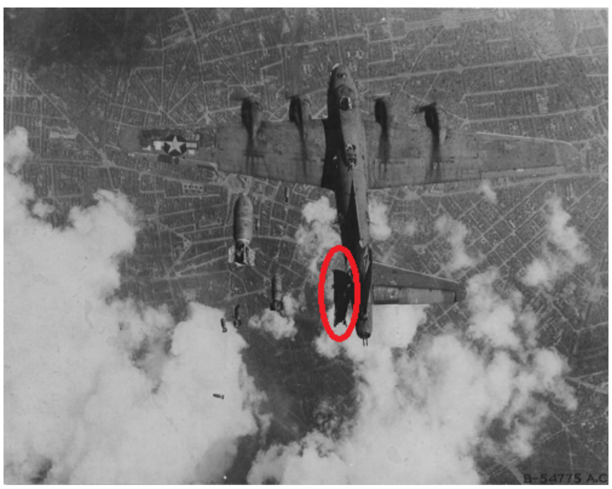
B. Missing Air Crew Report (MACR)

During World War II the United States Army Air Forces (AAF) required group units to submit Missing Air Crew Reports (MACR) to AAF headquarters within two days after an aircraft or air crew failed to return from a combat mission. The information contained in a typical MACR includes a date, time, and location that the crew and aircraft were last seen or reported missing from the formation. Details about aircraft incidents were taken from statements given by crew members from other aircraft flying in the same formation. These statements usually mentioned whether any parachutes were seen to have opened and how many airmen exited the aircraft before it crashed. The names of the missing air crew member(s) were listed by crew position, rank, serial number, and known status such as missing in action (MIA) or prisoner of war (POW). A MACR report was filed under number 4946 for this event. According to MACR 4946 [18] the aircraft was hit by a 1000 lb. bomb from an aircraft flying overhead in the high squadron. The tail section of this aircraft was broken off and the aircraft went down in what appeared to be a straight nose dive. One wing was observed to fall off when the aircraft was about 13,000 feet. This accident occurred directly over the target on signal

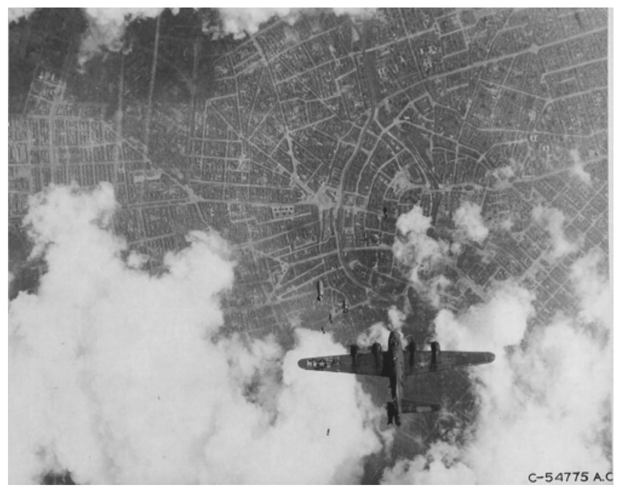
(a) Photograph showing stabilizer before bomb impact.



(b) Photograph 1 showing stabilizer after bomb impact.



(c) Photograph 2 showing stabilizer after bomb impact.



(d) Photograph 3 showing stabilizer after bomb impact.

Fig. 4 Photographs (a)-(d) showing the B-17G "Miss Donna Mae II" left horizontal stabilizer hit by bomb [17].

bombs away. According to the Report on capture of members of enemy air forces the aircraft crashed at 14:20 hours at Berlin N 58, Oderbergstrasse 38/39. According to the report filed by the German command the crash was presumably caused by flak damage. The aircraft was destroyed as a result of conflagration upon contacting the ground. Remains of 7 men were found which could be identified others were too badly burned.

C. Witness reports

Following research two witnesses were found to this event. One was a belly turret gunner in the formation who described the following [19]. “Mr Reid was on our left and a bit below us, I mentioned this to the crew. I figured he would stay there and be alright. For some reason he started drifting to our right and as he went under us I had to tell the bombardier to look down, there is an airplane right below us don’t drop. As the airplane went past us about that time bombs were dropped. The airplane above us, his first bomb came down very close to us between our wing and tail, Reid’s airplane was right under that bomb. And that bomb hit the left stabilizer. The airplane started to go down, never twisted or turned, straight down. The elevator was locked down, he didn’t know that at the time. Because pictures show he attempted to move the elevator back up by using the elevator trim tab”.

The second witness account comes from the Diary of Lt. Winslett, the captain who flew the B-17 "Trudy" which dropped the bomb onto the "Miss Donna Mae II". The following description is given of this event. “I started in the #6 position but Lt. Lukosus in the #3 position aborted early so I took over the #3 position in the formation. My bomb hit and knocked his (Donna Mae II) left stabilizer off and he went down. The ball turret gunner just said it was all clear and also the squadrons leader ball turret gunner had said the same."

VII. Scenarios

Historical records have shown that the B-17 has been able to fly home with significant damage sustained by for example flack. This leads to the question under which flight conditions (formation distance, gross weight, etc.) and bomb impact characteristics can the B-17 horizontal stabilizer be separated from the aircraft? Was the damage sustained by the bomb too great and beyond the B-17 stabilizer structural design? Can a calculation be made to determine a failure scenario?

After reviewing the photographs in Fig. 4 three main scenarios were developed which could explain the stabilizer failure. The first scenario will look at the possibility of an explosion of the bomb when it hit the stabilizer. The second and third scenario will look at the failure caused by bomb impact, where the distinction is made between a partial and a full separation of the horizontal stabilizer.

A. Left stabilizer separation due to the bomb exploding

When examining the photograph it is conceivable that a 1000lb bomb impacting a surface, like the horizontal stabilizer, could explode. In general an explosion would result in a three dimensional pressure wave. If this pressure wave was able to damage the horizontal stabilizer it would also very likely damage or even destroy the vertical stabilizer or tail fin of the aircraft. However in Fig. 4c, no damage can be observed on the tail fin despite the left hand side being visible. Furthermore the AN-M65 1000lb bomb has a nose and tail fuse. The standard nose fuse is Type AN-M103 and tail fuse is AN-M102A2. [20]. The tail fuse has a fail-safe mechanism and arms (using a propeller fuse) itself after 175 revolutions of the arming vane. The safe vertical drop for the nose fuse is 510-765 feet and the tail fuse is 465-665 feet [21]. The standard formation distance between the aircraft (height) would have been insufficient to arm the bomb before impacting the stabilizer. A closer inspection of photograph 4c, shows 5 visible bombs in a "train" which are above the clouds. Given the fact that five 1000lb bombs were carried on this mission by each B-17 entails that all the bombs are accounted for and thus none of them exploded. Scenario A, a bomb explosion upon contact with the left stabilizer, is assessed to be very unlikely.

B. Full separation of the left stabilizer by bomb impact

The second scenario that will be looked at is a full separation of the left stabilizer due to the bomb impact. This scenario has been suggested by several sources including the MACR[18] report and the original photograph descriptions Fig. 4. Following this scenario and given the time interval between the photographs it would be likely to observe the separated stabilizer falling down. Examining the three post impact photographs Fig. 4b, 4c, and 4d no debris can be observed. Evaluating this information Scenario B – full separation of the left stabilizer by impact is possible but given photographic evidence unlikely.

C. Partial Stabilizer separation of the left stabilizer by bomb impact

The third scenario that is considered is a partial separation of the left stabilizer due to bomb impact. By reviewing the B-17 stabilizer design the four terminal fittings (stabilizer-to-fuselage connection points), see 2, have been identified as the weakest link. Examination has shown that at this point all the forces and moments are transferred into the fuselage. It is proposed that the bomb impact could break one or more but not more than three terminal fittings. This failure scenario would break the two upper attachment points and the two lower attachment points would have sufficient strength to carry the stabilizer weight and aerodynamic loading. The sequence of this failure mode would be very elaborate as aerodynamic twisting and force loading may cause a multiple breaking scenario. Similar to scenario B the belly turret gunner who witnessed the event did not mention or provided any information pertaining to the stabilizer after it was hit by the bomb. Examining the post impact photograph Fig. 4b, 4c and 4d a black (shadow) structure, resembling part of the stabilizer can be seen hanging downwards from the tail section 4c. Subsequently, photographic evidence suggest a partial failure of the left hand stabilizer as a likely scenario and should be investigated further.

VIII. Structural modeling approach

In this paper the likelihood and validity of Scenario C – a partial separation of the left horizontal stabilizer, is chosen for examination. A benefit for selecting Scenario C is that it also implicitly incorporates the full stabilizer separation, Scenario B, if the outcome of the calculation would show this. The stabilizer construction will be idealized and the forces on the stabilizer will be considered statically. This will result in a simplified structural modeling approach. The idealized structural model should represent the stabilizer material behavior and mechanical properties especially for the four connections. As the horizontal stabilizer is designed to withstand the lift force during the most aggressive flight maneuver the idealized model should incorporate changes to the aerodynamic loading. Furthermore, the resulting forces and impact resulting from the bomb should serve as an input to the idealized structural model.

In conceptual design a simplified structural modeling approach is prospectively used to get early insight regarding layout and sizing of major structural members and components [22]. This analytical method can also be applied retrospectively to assess the likelihood and failure mode of a structural member or component given actual inputs based on evidence. It is known that such analytical methods are conservative. Therefore, if this method supports the failure scenario, it is very likely that more detailed, accurate, and, by construction, less conservative analysis will draw the same conclusion.

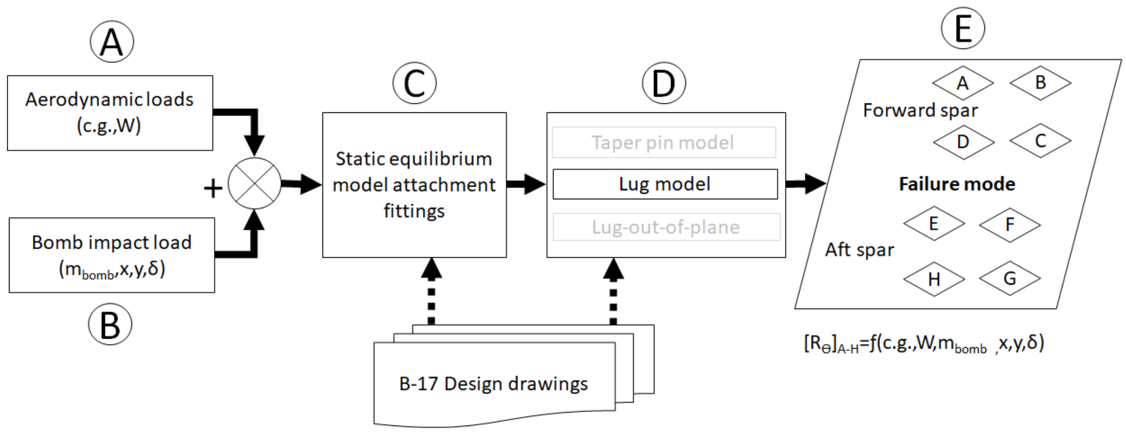


Fig. 5 Structural modeling approach diagram.

Figure 5 shows the model setup with the inputs consisting out of the estimated aerodynamic loads Ⓐ and the force resulting from the bomb impacting the stabilizer Ⓑ. The stabilizer static equilibrium model for the connection points Ⓒ represents the mechanical characteristics of the stabilizer connection points to the main fuselage. In the failure model Ⓓ the taper pin, lug and male fitting connection base maximum forces are calculated. The analytical model was created using B-17 design drawings and component specifications [23]. Given model inputs an assessment of possible failure mode(s) Ⓔ can be evaluated. A more detailed description of the modeling approach is provided in the next sections.

A. Vertical aerodynamic loads

For a balanced flight condition, the external forces and moments acting in the vertical plane on an aircraft can be determined using the simplified scheme depicted in Fig. 6. The B-17 aircraft can be simplified to a fuselage, main wing and stabilizer. The aircraft weight ($W_{c.g.}$), lift (L) and the stabilizer force ($F_s tabilizer$) are assumed to be aligned in the Z-direction. A balancing calculation can be executed to determine the stabilizer vertical force or lift. Using the aircraft weight and balance data the center of gravity (c.g.) and mean aerodynamic chord (mac) are described [24]. As the B-17s' center of gravity and weight range are known the load balancing calculation Eq. (1) and Eq. (2) yields the stabilizer vertical force for its full operational flight range. The balancing calculation output is the total stabilizer force or vertical force created by the stabilizer during flight.

$$\sum F_Z = L - W_{c.g.} + F_{stabilizer} \tag{1}$$

$$\sum M_{X\,c.g.} = F_{stabilizer} \times arm_{stabilizerforce-c.g.} - L \times arm_{Lift\,c.g.} \tag{2}$$

The total stabilizer aerodynamic resultant vertical force needs to be redistributed based on the wing planform. A good approximation for the B-17 stabilizer planform is an elliptical lift distribution [25]. Given the elliptical lift distribution, the stabilizer lift center of mass is located at 3/8 (Y-direction) half span from the stabilizer root creating a moment M_x. The B-17 stabilizer uses a NACA 0012 symmetrical profile which can be assumed to have an assumed aerodynamic center at 25% chord. Using the average profile chord length, the centers of mass of the vertical force in X-direction will result in a M_y moment.

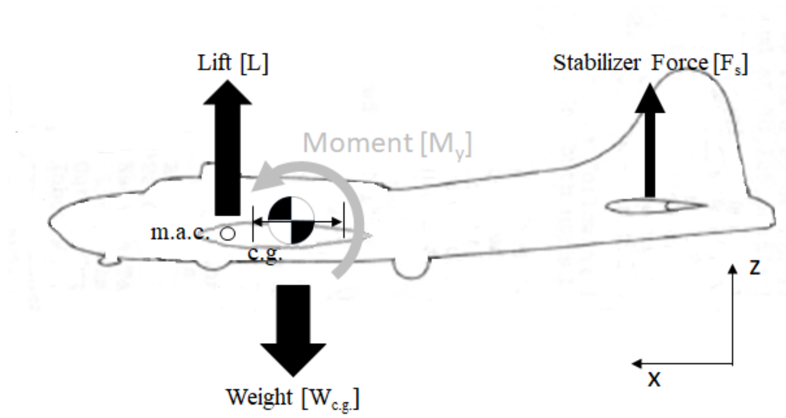


Fig. 6 The vertical forces and moment for the B-17 weight and balancing calculation

B. Bomb impact load

Impact force is the result of contact and deformation between the impacting object and target structure. From the work-energy principle the impact force can be derived using potential energy Eq. (3) combined with the work equation Eq. 4 resulting in Eq. (5). Where F_{impact} is the average force exerted during contact and δ is the distance traveled by the impacting object during contact and deformation.

$$E = m \times a_g \times h \tag{3}$$

$$W = F_{impact} \times \delta \tag{4}$$

$$F_{impact} = \frac{m_{bomb} \times a_g \times h}{\delta} \tag{5}$$

Where h is the altitude difference between the two aircraft when the bomb was dropped. To solve for impact force F_{impact} using Eq. (5) three variables need to be established. The first variable is the mass. The bomb which can be seen hitting the stabilizer in Fig 4a was identified as an AN-M65 bomb weighing 1000 lb. The second variable is the drop height h or falling distance. For this paper the falling distance will be assumed to be the height difference between the high squadron aircraft #2 and lead squadron #5 flying the box formation which is 50 feet as shown in Fig. 3 Estimating the impact distance δ over which F_{impact} acts is a major challenge. The distance is limited by elastic and plastic deformation and stiffness of the target structure around the impact point. It is also affected by the specifics of failure of the part of the structure in contact with the impacting object. Ribs would fail in a different way than spars for example, leading to different values for δ. More elaborate models of the contact force and its evolution during impact will be introduced in future research. Making a reasonable estimate will entail a more detailed structural analysis which is beyond the current paper scope. Therefore, the impact distance δ will be considered as a variable input parameter. It is assumed that the maximum distance δ is half the wing profile thickness. It is expected that after the impacting object has traveled that distance, the dynamic effects make further failure progression nearly instantaneous and F_{impact} drops to almost zero.

Two other model input variables are the X and Y-coordinate of the bomb impact point on the stabilizer. Using Fig. 4a an estimate of the bomb impact location can be determined using scaled distances. Figure 4a is a top view of the B-17, where the Bomb c.g. is at 1/3 from the nose. Assuming no lateral movement occurred before impact the impact location is determined to be approximately 35 inches (Y-direction) from the fuselage-stabilizer root connection. This result will be used to evaluate the model outcomes for the photographed stabilizer impact event.

C. Static equilibrium model connection points

The two-spar horizontal stabilizer consists of a center structural box section with two outer sections, the leading edge section and aft elevator section. The aft spar serves as the connection point for the elevator. The leading edge consists of the ribs shaping the nose which are connected to the forward spar and the skin. It is assumed no major structural load can be carried by leading edge because it is designed for much lower loads than the bomb exerts during impact and thus would fail immediately. The elevator is a separate element connected by two hinges and a torsion bar for elevator and trim control. Similar to the nose section the elevator is considered to to able to carry a bomb impact load and would fail immediately. As such this approach uses a symmetrical structural box section consisting out of the forward and aft spar to assess the forces and moment at the stabilizer root to fuselage connection. As a result, the bomb impact location (X and Y-direction) which is a model input should be within the wing box outline shown in Fig. 2. This is supported by close examination of Fig. 4a.

The horizontal stabilizer is in principle designed to withstand the lift force and is connected to the fuselage by two terminal fittings on each spar. Each terminal fitting consists of a male and female lug system with two holes for a taper pin Fig. 2 detail A. The fittings have lug holes which are individually designated from A-H. Using the wing box dimensions the reaction forces F_x, F_Y and F_z of each individual lug hole can be calculated following the aerodynamic Ⓐ and bomb load Ⓑ inputs.

D. Taper pin and Lug model

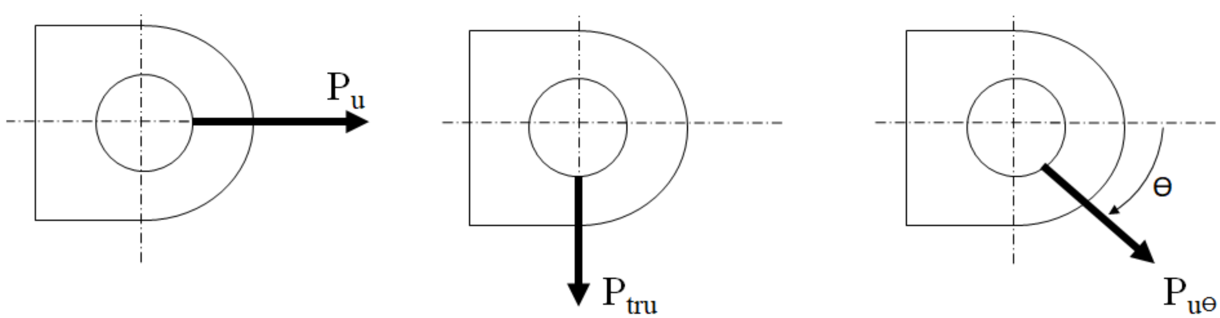
The taper pin and lug models are required to establish maximum loads that can be carried by the connection. The lug model will describe the maximum load the lug connection is able to withstand. The dimensions and material specifications are based on B-17 design drawings. Once the maximum loads have been established the failure likelihood and mode can be established by using the results of the calculated static equilibrium forces. The taper pin model will describe the pin shear failure.

The maximum or ultimate taper pin load $P_{u-taper-pin}$ can be calculated using Eq. (6) [26–28]. As the shear area is on both sides of the taper pin connection the total shear area is double the taper pin area A where $F_{u-taper-pin}$ is the taper pin ultimate shear strength.

$$P_{u-taper-pin} = F_{u-taper-pin} 2A \tag{6}$$

Equation (7) is used to determine the pin ultimate bending load assuming uniform bearing across the lug [26–28]. The t_1 and t_2 are the thicknesses of the male female connection, D_p is the diameter of the pin connection and the plastic bending coefficient K_{bp} is assumed to be 1.56 to reflect ductile material with 5% elongation.

$$P_{ub-taper-pin} = \frac{0.193 K_{bp} {D_p}^3 F_{u-taper-pin}}{t_1/2 + t_2/4 + g} \tag{7}$$



(a) Axial ultimate load **(b) Transverse ultimate load** **(c) Oblique ultimate load**

Fig. 7 Lug loading.

The maximum load able to be carried by the lug connection can be calculated using standard calculation methods [26–28]. Three different load cases can be distinguished an axial, transverse and an oblique load failure Fig. 7. For axial load failure three failure modes can be distinguished, a net section failure which can be described by Eq. (8), a shear-out or bearing failure which can be calculated by Eq. (9).

$$P_u = K_t A_t F_{tu} \tag{8}$$

$$P_u = K_{br} A_{br} F_{tu} \tag{9}$$

A transverse failure load is predicted by Eq. (10), where the reduction factor is a function of the area. Where A_{br} is calculated using the lug dimensions and K_{tru} is calculated but a function that is dependent on the lug geometry. Where K_{tru} is a function of A_{av}/A_{br} using established procedures [28], the efficiency factor for transverse loading can be found and the allowable transverse load can be solved for.

$$P_{tru} = K_{tru} A_{br} F_{tu} \tag{10}$$

The approach to calculate the strength of lugs under oblique load is to resolve the applied load in axial and transverse components R, where R is the ratio of the applied over allowable load in its respective direction. Using this relationship an interaction curve K_{bru} can be obtained using Bruhn [28].

$$R_a{}^{1.6} + R_t{}^{1.6} = 1 \tag{11}$$

Equation (11) is a convenient approach to determine the lug failure mode as both the axial and transverse forces are united into a resultant R_θ. When R_θ is located outside the calculated interaction curve, failure will occur. Using this equation in the model as an output will thus yield the answer to a lug failure mode and direction.

A third failure mode that is considered is a lug-out-of-plane loading resulting in a fitting failure. The male lug connection will be loaded in X-direction (see Fig. 2) resulting in a shear force and a bending moment. Substituting stress criterion Eq. (13) in Eq. (12) and given the lug material properties the maximum applied F_x can be derived. By using Eq. (14) the maximum normal stress capability can be calculate for the applied load F_x. This yielding two maximum $F - X$ forces given in table 1

$$\tau = \frac{3}{2}\frac{F_X}{tw} \tag{12}$$

$$\tau_y = \frac{1}{\sqrt{3}}\sigma_y \tag{13}$$

$$\sigma_y = \frac{3}{2}\frac{F_X dt 12}{2wt^3} \tag{14}$$

Table 1 Calculated thresholds F_x based on the lug maximum shear and normal stress.

	Shear stress	Normal load
F_x	206738 N	45471 N

As this study is a first step into future research for simplicity only the lug oblique load F_θ failure mode is considered. Using the B-17 design drawing and material specifications the axial ultimate load P_u and the ultimate transverse load P_{tru} for each fitting connection of the forward spar $(A - D)$ and aft spar $(E - H)$ were calculated resulting in Table 2.The lug ultimate loads of the outside elements $B - C - F - G$ have a lower axial load capability as they are close the lug edge.

E. Failure mode

Using Eq. (11) and Table 2 lug failure threshold for each connection element $A - H$ can be determined. The calculated forces Ⓒ of each lug element are used to calculate the R_θ for each lug element and compared to the established threshold Ⓓ. By using the threshold the the lug element failure mode Ⓔ can be determined.

Table 2 Calculated ultimate lug load thresholds for fittings

Fitting	Axial load	Transverse load
A-D-E-H	394825 N	132151 N
B-C-F-G	267070 N	132151 N

IX. Results

A parametric study was performed varying the bomb impact location (X- and Y-coordinates), bomb mass and the impact distance δ. The bomb impact location was varied from the minimum and maximum X- and Y-coordinates within the wing box planform. The impact distance δ was varied from 0.5 to the assumed maximum of half the spar thickness of 4 inches. The δ values were plotted as negative to indicate the impact distance from the top of the stabilizer $z = 0$ downwards. The aerodynamic loads were based on a B-17 flying in symmetrical flight conditions where $W_{c.g.}$ and c.g. are within the aircraft flight envelope. The c.g. was assumed to be at $25\%mac$ which according to the weight and balance calculation results in a $F_{stabilizer} = 2000N$ load. To make the calculation results insightful a red dot was plotted in case the maximum oblique lug load R_θ was exceeded, a green dot was plotted in case the oblique load threshold was not reached.

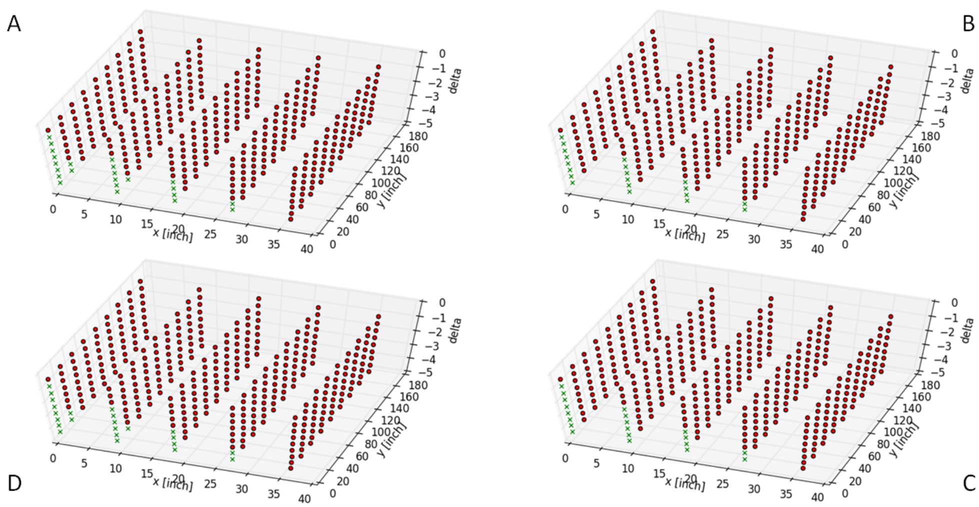


Fig. 8 Oblique load failure for lug element A-B-C-D ($m_{bomb} = 1000lb$, F_s=2000N).

As can be seen from the Fig. 8 and 9 where $m_{bomb} = 1000lb$ a small area exists where the oblique lug load is not exceeded, this is near the root at large δ values. Reducing the bomb mass to $m_{bomb} = 100lb$ shows an increase in area where the lug load is within the R_θ threshold as shown in Fig. 10 and Fig. 11. This is also the case when the bomb is dropped at $y = 35$ inches, the estimated impact location from Fig. 4c. In this case however the calculated resultant F_x for fitting D and E are beyond the established normal load threshold for impact distance $\delta = 0.5$ and a failure would still occur.

Assuming a bomb impact location on the forward spar $x = 36$ inch, an impact distance $\delta = 1$ and varying the bomb masses m_{bomb} which can be carried by the B-17 will result in Fig. 12. It can be concluded that a small area will not result in failure of the horizontal stabilizer and the lug load is within the R_θ threshold. What should be noted is that in this case the R_θ threshold is not exceeded for a $m_{bomb} = 1000lb$ when the bomb impacts the aft spar ($x = 0$).

X. Discussion

The model results show that in most cases a $m_{bomb} = 1000lb$ would separate the stabilizer as shown in Fig. 8 and 9. This finding is not entirely consistent with the photographs of the event Fig. 4. By reducing the bomb mass to $m_{bomb} = 100lb$ the same study was performed. What one concludes from 10 and 11 is a relatively narrow range of impact locations exist where R_θ is above the threshold and the stabilizer would separate. A reverse outcome compare to

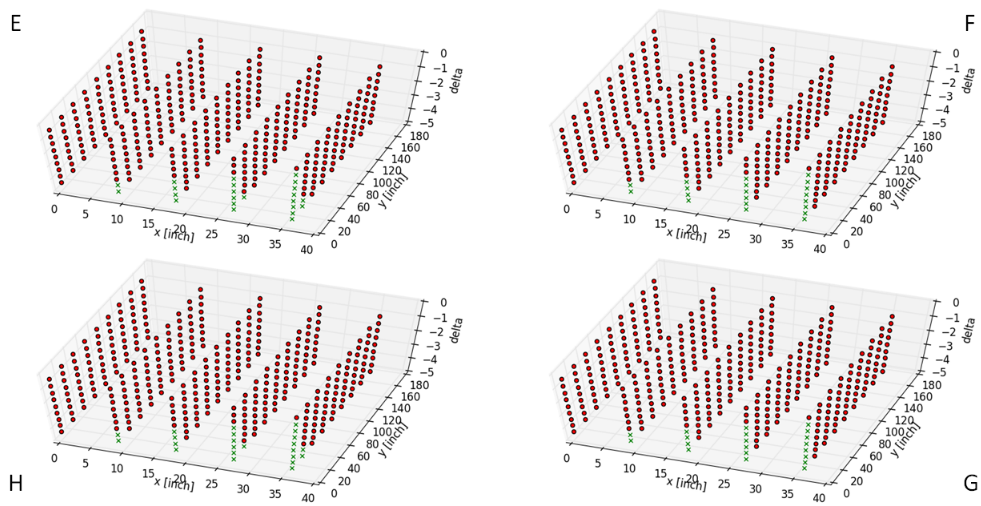


Fig. 9 Oblique load failure for lug element E-F-G-H (m_{bomb} = $1000lb$, F_s=2000N)).

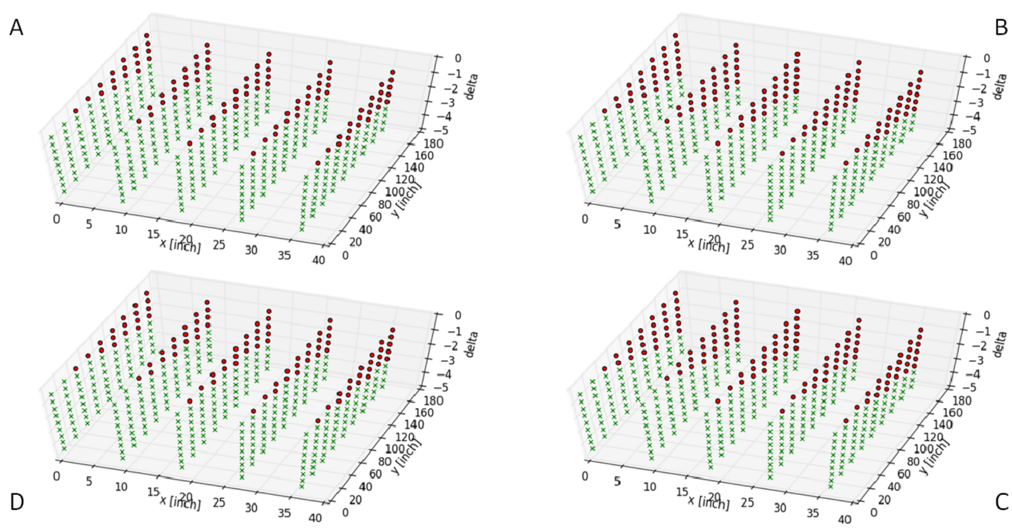


Fig. 10 Oblique load failure for lug elements A-B-C-D (m_{bomb} = $100lb$, F_s=2000N).

m_{bomb} = $1000lb$, which shows that m_{bomb} mass influences the lug failure mode. Similar to Fig. 12 where the bomb mass m_{bomb} was simulated to vary the study outcome shows a small area where the stabilizer would not shear off. However this calculation shows the result of the forward spar when the bomb impacts the aft spar. This is an ideal case which is not consistent with Fig. 4a where it was estimated that the bomb impact was at y=35 inches between the forward and aft spar. Figure 8 and Fig. 9 clearly show that in that case the R_θ threshold was exceeded. Thus for the vast majority of cases it is expected that the stabilizer would separate.

By inspection the most likely failure points of the horizontal stabilizer were identified as being the lug connection points at the forward and aft spar fitting. As the focus of this study was on the lug connection alternative failure modes were not considered and studied. Future research and structural model improvements may identify an alternative failure as forces and load interactions after impact can be complex. As shown in Fig. 8 where at one point the axial and transverse lug loading are within the established threshold but another failure mode threshold F_x was exceeded as calculated in table 1. Thus the resulting forces from a bomb impact are complex and therefore each threshold needs to be identified and addressed separately for a valid failure determination.

For this approach each lug fitting was individually modeled for simplicity and the interaction between the two lug fittings have been ignored. It is conceivable that due to 1.25-inch distance between the lug holes a local stress

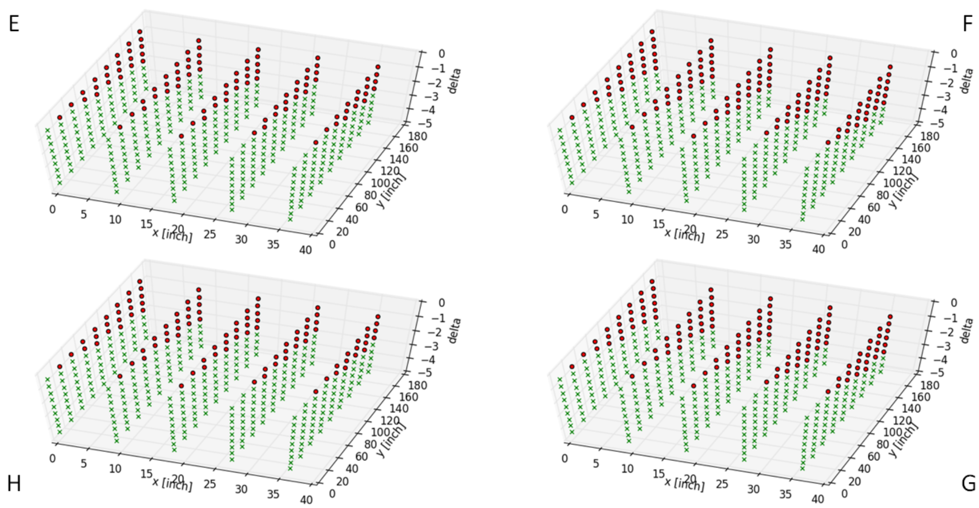


Fig. 11 Oblique load failure for lug element E-F-G-H ($m_{bomb} = 100lb$, F_s=2000N).

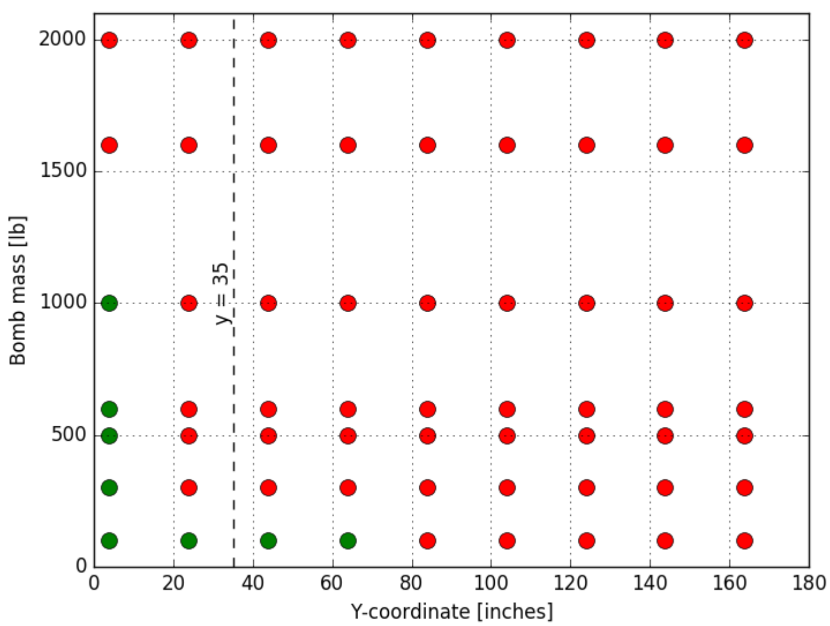


Fig. 12 Forward spar with varying bomb mass m_{bomb} and y-coordinates ($F_s = 2000N$, $\delta = 1$, x=0).

concentration interaction is conceivable. As such an oblique load with large θ or transverse load may result in earlier failure than is currently predicted.

The structural modeling approach as described is conservative and the results may over estimate the reaction of the stabilizer. The F_{impact} is highly depended on the impact distance. The F_{impact} is modeled as a point load which is also not realistic for impact which would spread and the impact energy can dissipate over a larger area which causes reduced forces. Future research is required to enhance the structural modeling fidelity hereby increasing the failure mode determination validity.

XI. Conclusion

This paper has given an overview of the B-17 Flying Fortress design, development and production. The B-17 bomber aircraft was used extensively in World War II and flew many bombing missions. On May 19^{th}, 1944 during one of these missions a B-17 horizontal stabilizer was hit by a bomb released form another B-17 flying in formation above. According to records the horizontal stabilizer separated and the aircraft was lost. The event description was based on witness accounts and photographs taken that day. Given the B-17 reputation to return home even when being badly damaged as has been recorded in history begs the question, was the bomb impact beyond the B-17s horizontal stabilizer structural design limit? This event was never examined from a forensic engineering standpoint looking at the B-17 structural design and using different information sources.

Using B-17 drawings a horizontal stabilizer structural model was created incorporating material and structural properties. The model considers the effects of forces, moments and torsion resulting from bomb impact and the horizontal stabilizer aerodynamic loading during flight. The study focused on the forward and aft spar fittings which connect the horizontal stabilizer to the fuselage. By inspection these connections points which consist of male and female lug fitting were determined to be the most likely failure locations following bomb impact. Additionally, for simplicity the failure model only considered lug loading.

A parametric study was performed varying the bomb impact location and bomb mass given normal B-17 flight conditions to determine if lug load thresholds were exceeded. The preliminary outcomes show that under a wide range of possible input parameters used in this study, the stabilizer would separate. Analyses of the event photographs however show that a full separation did not occur. As the developed structural modeling approach is conservative future research is required to enhance the impact model and reaction forces on the connection fittings which were identified as the most likely failure points. This improvement will better determine the failure mode and possible interaction that may occur during a dynamic loading following impact which has not been considered. As only oblique lug loading was considered for failure future research should incorporate other modes for completeness. The simplified construction model was based on a symmetrical wing box with a forward and aft spar similar in height and length, this is however not exact. The aft spar is longer and smaller in height compared to the forward spar. The later difference will alter the structural equilibrium which results in different forces and moments which in turn may change the fitting failure mode.

The analysis of different bomb impact locations shows that the approach works but it is limited on its accuracy due to the assumptions made. Future developments to address the issues provided in the discussion section have the potential to increase model validity and improve the failure mode identification of the B-17 horizontal stabilizer shown in Fig. 4. Therefor it is likely to learn more from the in-flight structural failure by conducting future research and forensically applying structural modeling to re-engineer history.

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