IMPLEMENTATION OF RELIABILITY CONCEPTS IN STRUCTURAL DESIGN CRITERIA

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ABSTRACT

The historical development of structural design criteria is briefly sketched. The manner in which past criteria met six objectives of structural design criteria is noted, and some anticipated changes that may invalidate the previously successful procedures are indicated. The concept that three discrete levels of reliability must be considered is introduced together with an Ingredients chart showing the elements of satisfactory criteria. It is noted that classical statistical theory is incapable of a complete solution to the problem, and a Bayesian approach is recommended to cope with the situation realistically. Individual definition of limit and ultimate conditions is recommended to meet separate requirements which are not connected by a factor of safety. Appropriate strength and loads testing is recommended to demonstrate both limit and ultimate reliability.

INTRODUCTION

Reliability concepts have been recognized in the structural design of aerospace vehicles since antiquity. According to Greek mythology, Daedalus built wings of wax and feathers so that he and his son, Icarus, could escape from Crete. Icarus boldly flew too close to the sun, the wax in his wings melted, and he plunged into the sea—the first recorded aerospace structural failure. The severity of Icarus' environment exceeded the capability of his structure. On the other hand, Daedalus flew more conservatively and survived.

At this point in history, the demonstrated reliability of flight was only 0.50. Undoubtedly, if this type of flight had continued, the reliability of the operation would have improved. Daedalus helped define the boundary between survivable conditions and disaster, and even foolhardy Icarus increased man's knowledge. As Sir Arthur Eddington [1] has pointed out, Icarus "brought to light a serious constructional defect. . . . Cautious Daedalus will apply his theories where he feels confident they will safely go; but by his excess of caution their hidden weaknesses remain undiscovered. Icarus will strain his theories to the breaking point till the weak joints gape. . . . We may at least hope to learn from his journey some hints to build a better machine."

We in the aerospace industry have learned to build better machines; if these are to be efficient machines, we must continually strain our theories to the breaking point.

DEVELOPMENT OF STRUCTURAL DESIGN CRITERIA

The first real instance of a catastrophic structural failure in aviation history occurred about five years after the Wright brothers' first flight. The Wrights were demonstrating the capability of their latest airplane to carry a passenger. During this demonstration Orville Wright "suddenly heard an ominous tapping sound behind him. He turned his head and . . . saw that a propeller blade had splintered and cut vital control wires" [2]. Lt. Thomas Selfridge was fatally injured and Wright seriously hurt.

The Wright brothers were aware of the need for adequate structural design criteria for their airplanes. As disclosed by Hoff [3], one of the brothers wrote to his father that they had designed their airplane to withstand five times its own weight.

Civil requirements in the United States originally specified ultimate load factors based on an assumed method of aircraft operation. An inherent weakness of the early criteria was the failure to specify restrictions and placards to ensure the assumed operation. In the event of an accident, the corrective action was not obvious because operational causes were not easily separable from structural causes. Correction of this problem began in 1934 when factors of safety (F.S.) were established as a criteria concept.

By the standard of general acceptance, the present criteria system has been successful. On those rare occasions when failures have occurred, changes were instituted in response to the difficulties. It has been a completely pragmatic approach. As a result, tomorrow's vehicles are always designed to overcome yesterday's problems.

A shortcoming in the present system is that there is no logical mechanism for making decisions on whether to change or retain particular criteria. In other words, there are no criteria for the criteria. Factors of safety selected for missiles and spacecraft have varied from 1.25 to 1.35 to 1.4 and up to 1.5, as judgment dictated. Furthermore, many anomalies have developed unintentionally. Mangurian [4] showed that the factor of safety needed to sustain a gust 50 percent above the limit gust velocity varied from 1.20 to 1.62.

Present criteria require that the internal stresses resulting from ultimate loads be less than allowable stresses specified in documents such as Ref. 5. If this requirement is met, the structure has a positive margin of safety and is considered safe. This deterministic approach has fostered the false concept that all structures are either safe or unsafe.

CRITERIA OBJECTIVES

There are no absolutes in structural design. The only way to prevent "all" failures is to make the structure infinitely strong—and therefore infinitely heavy. Since structures are not permitted to be infinitely heavy, the question to be answered is: How weak can we design our structures without incurring the risk of "too many" failures? To best understand how reliability concepts can answer this question, one must understand how reliable structures have resulted from past structural design criteria, ostensibly without the need for any statistical considerations. But first, the basic objectives of structural design criteria should be stated:

1. Define a satisfactory and consistent level of structural strength for the vehicle, considering its intended mission plus alternate or anticipated missions.
2. Define operational limits to the user.
3. Provide an administrative tool to decide the issue of structural compliance or noncompliance with vehicle specifications.
4. Provide a decision-making mechanism in the event of a structural failure for allocating responsibility for causing the failure.
5. Establish the criteria for the criteria so that it can be decided when a change is necessary in the structural design criteria.
6. Specify criteria that can be implemented by the existing state of the art.

STRUCTURAL RELIABILITY CONSIDERATIONS

The reliability approach to structural design criteria can be better understood by considering one of the simplest of all structural systems—a known weight supported by a tension rod. If the ultimate load on the rod is equal to or less than the allowable strength (that is, the allowable stress times the area of the rod), the structure is considered safe. Figure 1 shows what has been accomplished statistically by this procedure. Reference 6 shows that the probability of failure (P_F) at the limit or actual load is 10^{-50} if: (1) the F.S. is 1.5; (2) the strength distribution is Gaussian; (3) the coefficient of variation, γ, is 0.025; and (4) the typical allowable stress presented in Ref. 5 corresponds to the 99-percent exceed stress.

The weight-on-the-rod problem is presented because it is easily understood and contains most of the elements of the real problem. Only a change in the loading from a single deterministic value to a load defined probabilistically is needed to complete a realistic picture. With a typical load distribution and small strength variance, most failures will be concentrated in a narrow region between the allowable strength and the mean strength, as shown in Fig. 2. The P_F increases from 10^{-50} to about 10^{-7} when the probability of exceeding (P_E) the ultimate load is 10^{-6}. If P_E were 10^{-2}, P_F would increase to approximately that value.

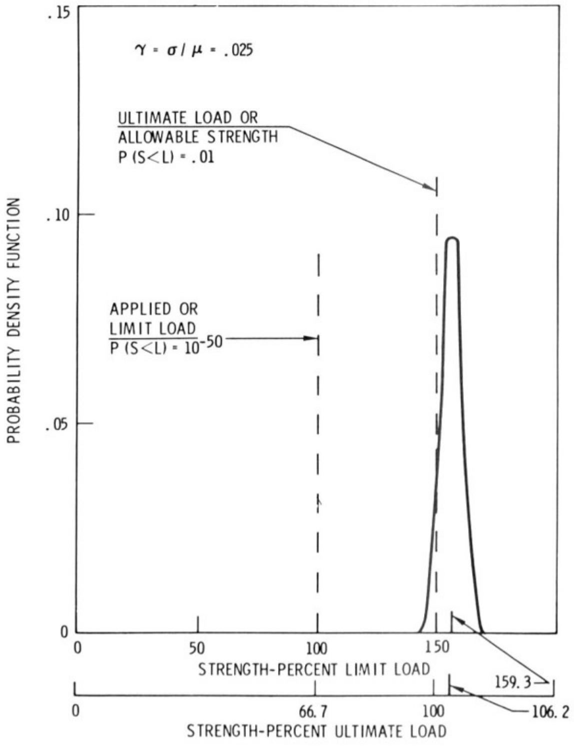

Figure 1. Failure distribution—simple system.

Consideration will now be given to the effect a large increase in γ has upon structural reliability. Figure 3 shows that if the problem in Fig. 1 is changed so that the variance of the single member is 0.25 (ten times that of the Fig. 1 example), the P_F increases from 10^{-50} to 2×10^{-3}. A failure rate of 1 in 500 at limit load would not be acceptable in most situations. This is the intuitive basis for rejecting castings and other brittle materials for use in aerospace structures.

Next to be considered is a multi-element chain supporting a weight. If one of the links has a large variance in strength and the N other links are all small variance, some interesting observations can be made. For example, if the structure is adjusted so that $P_F = 0.01$ at ultimate for every value of N, then P_F at limit decreases with N, as shown in Fig. 3. In this special case, the more elements in the structural system, the more reliable it is!

Another example is a multi-element chain subject to a loading spectrum for a low-risk vehicle such as a transport aircraft. The probability of failure is calculated for strength variances of five, two, and zero percent. These are normalized and shown in Fig. 4 versus the number of components. Another curve is calculated for a load spectrum representative of a high-risk vehicle such as a fighter airplane. The earlier example, in which the reliability increased with the number of elements, is added for comparison. It is apparent that the probability of failure is increasing less rapidly than

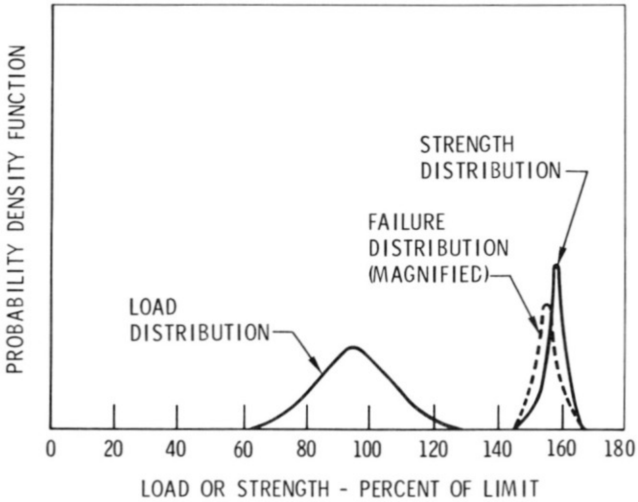

Figure 2. Failure distribution—simple system, random load.

the number of components. Since the probability of failure does not increase in proportion to the number of components in a structure and may even decrease, the allocation of a proportionate share of the total unreliability to each component, as advocated by so many [7,8,9], is statistical nonsense.

To help document the case for reexamining more of our statistical shibboleths, this final example is cited. It involves the commonly accepted belief that redundancy improves reliability. If the simple system presented earlier is modified so that the structure consists of two equal-area, concentric tubes, the structure is redundant but not necessarily more reliable. If the material is brittle, the P_F of the system is about twice that of the individual member. If the material is ductile, the mean of the two-member system is unchanged and the variance is reduced. The relationships are shown in Fig. 5.

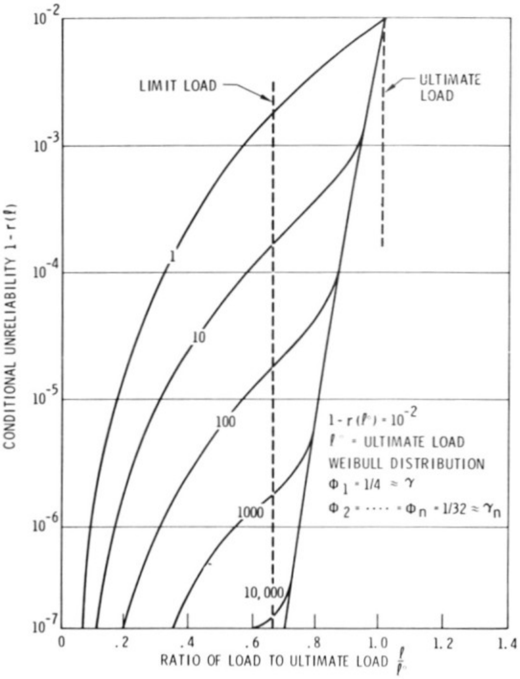

Figure 3. Multi-element structure ($P_{F_{ULT}} = 0.01$).

The examples presented illustrate some little-understood aspects of the structural reliability problem. The era of supersonic and hypersonic flight of aircraft and spacecraft will require structures that are incompatible with the previous class of structures for which structural reliability could be attained indirectly. Under these circumstances, we can neither consider as sacrosanct our past procedures nor expect to solve the problem with unsophisticated applications of classical statistical theory.

INGREDIENTS OF STRUCTURAL DESIGN CRITERIA

THREE RELIABILITY LEVELS

It is postulated that there are three distinct types of failure, as shown in Fig. 6. Objective 1 implies a satisfactory level of reliability for all three. The first failure mode to consider is yield. In this paper, yield represents

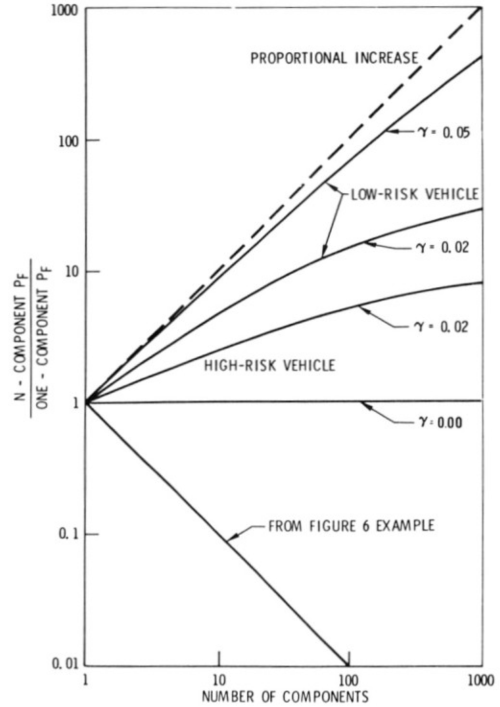

Figure 4. Normalized P_F versus number of components.

those failures resulting in permanent set but which are not catastrophic. Yield failures are not considered further in this discussion except as they act to disclose errors.

The second mode of failure is catastrophic rupture at limit conditions or less. This has not been considered explicitly in the criteria of the past since a sufficiently high reliability against this type of failure has been attained by indirection. The combination of an F.S. and a material allowable does not ensure any particular level of reliability at limit conditions. As shown previously, the restriction of aerospace materials to those with small variance results in high reliability at limit conditions. As some of these restrictions are removed to provide structure which will meet the new environmental conditions, the criteria must make explicit provisions for limit-type reliability. The requirement can be verbalized as a provision against unexpected failures at expected conditions.

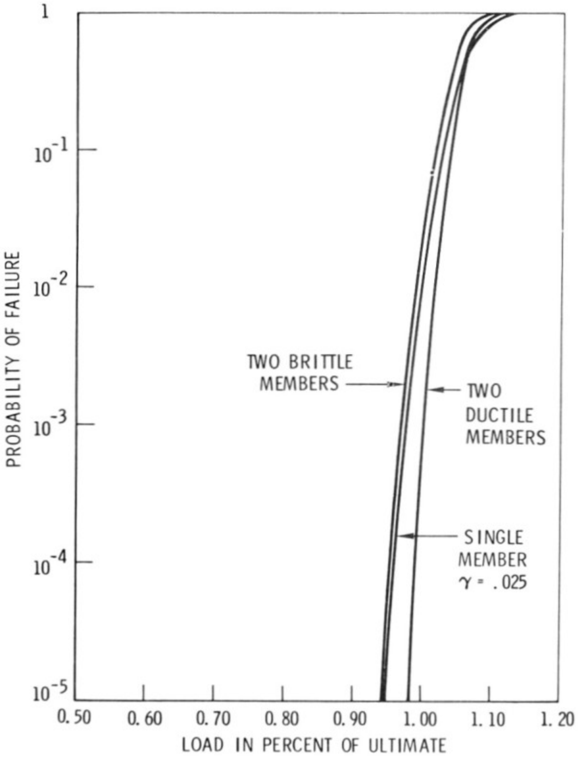

Figure 5. P_F of redundant system.

With regard to the definition of limit load, it should be noted that any condition within the specified operating limits must be considered as expected, even *if* the condition is rarely encountered. In effect, a conditional reliability requirement is being specified; the reliability of the system must be very high if the condition is ever encountered.

The third failure mode illustrated in Fig. 6 is characterized by catastrophic failure at ultimate conditions. There are two statistical functions involved here. One is the conditional reliability reflecting P_F at ultimate conditions. Typically, this reliability approximates 0.99, so that "most" of the structures survive ultimate conditions. The other statistical function associated with ultimate design is the probability of equaling or exceeding the ultimate condition. If the strength variance is low and if the conditional reliability is 0.99, the cumulative P_F in the structural system approximates the P_E of the ultimate condition. This close association between P_F and P_E of ultimate is a major factor in the success of present criteria. Although

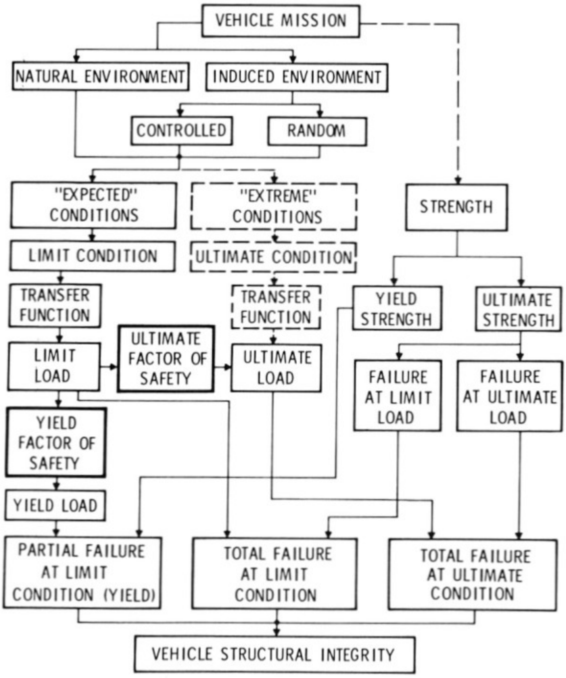

Figure 6. The three levels of structural integrity.

both combat aircraft and military transports may have the same conditional reliability at ultimate, the overall reliability of the first may be 0.99 and the other 0.999999. Furthermore, strength requirements are associated with the conditional reliability and operational considerations are associated with the P_E of ultimate. As a result, it is relatively simple to identify the function in error whenever a failure occurs.

MAJOR CRITERIA ELEMENTS

The major criteria elements necessary to develop the reliability levels discussed above are outlined in Figs. 7 and 8. Some judgment of the future is required to establish a new criteria. Then, structural design analysis is performed to determine whether a particular configuration meets the requirements. Structural tests and operational loads tests are formulated to disclose and eliminate any error in the structural design analysis. This results in a high reliability for the specified conditions. Actual operations are required to disclose whether the design conditions are properly specified in the criteria. If all of these steps are properly accomplished, no change is required and the criteria are satisfactory. These steps are discussed in detail below.

Judgment of the Future. New structural design criteria must be established on the basis of a judgment of the future. This judgment is formulated both from old and new knowledge. Although the objective of criteria is to define a satisfactory level of structural reliability, criteria cannot be based on classical statistics because we never really have enough data. The number of airplanes in a fleet are never more than in the thousands and often are in the hundreds. In the future, spacecraft will be numbered in the tens. The permissible unreliability is usually so near zero that it cannot be evaluated with any degree of confidence.

If we cannot define structural reliability by use of classical statistical theories, must we depend entirely on personal judgment? It is suggested that a Bayesian approach [10] might be the solution. By adopting the Bayesian attitude, it becomes sensible to combine old and new knowledge together with some reasonable assumptions to form a judgment of the future.

Establishment of New Criteria. Past criteria have been developed on the basis that failures should be very infrequent. While it has been argued that the design objective should be "no" failures, aerospace structures have never been expected to tolerate gross errors in other systems. As Christenson says, "Design for safety does not mean pure brute strength without regard for economic feasibility" [11]. Criteria must be established with realistic understanding of what we expect to accomplish.

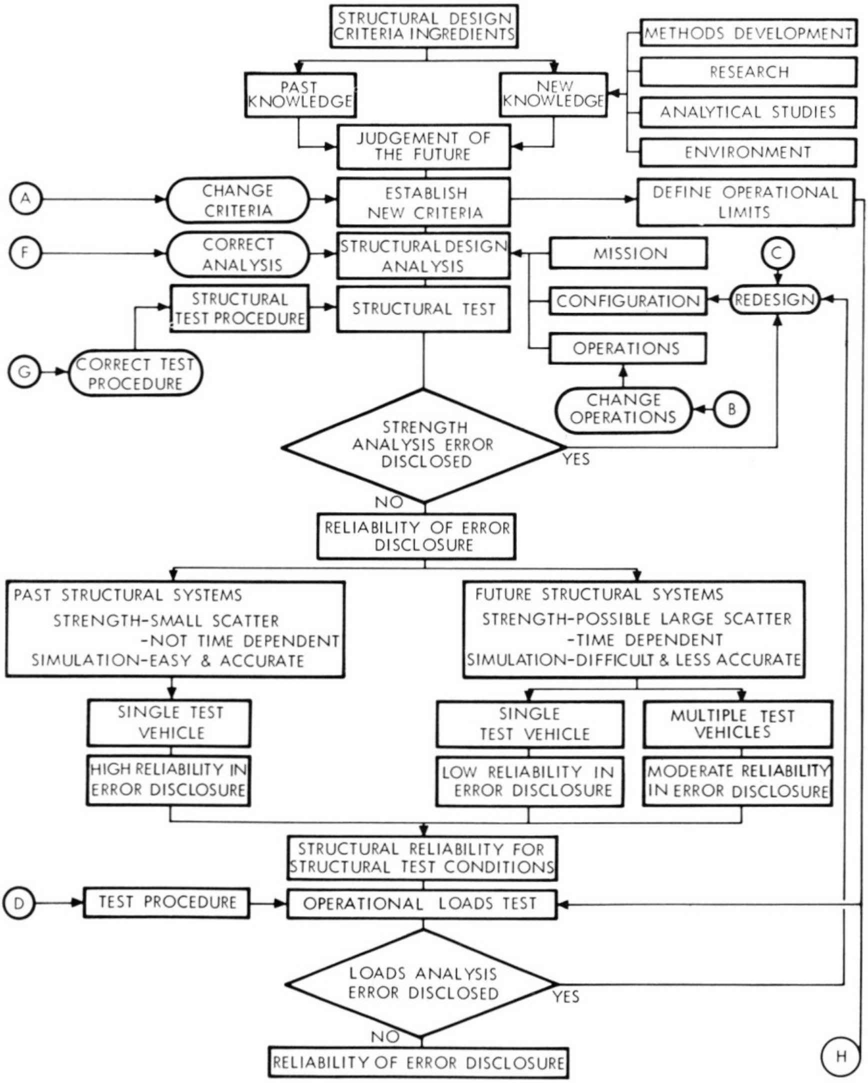

Figure 7. Structural design criteria ingredients.

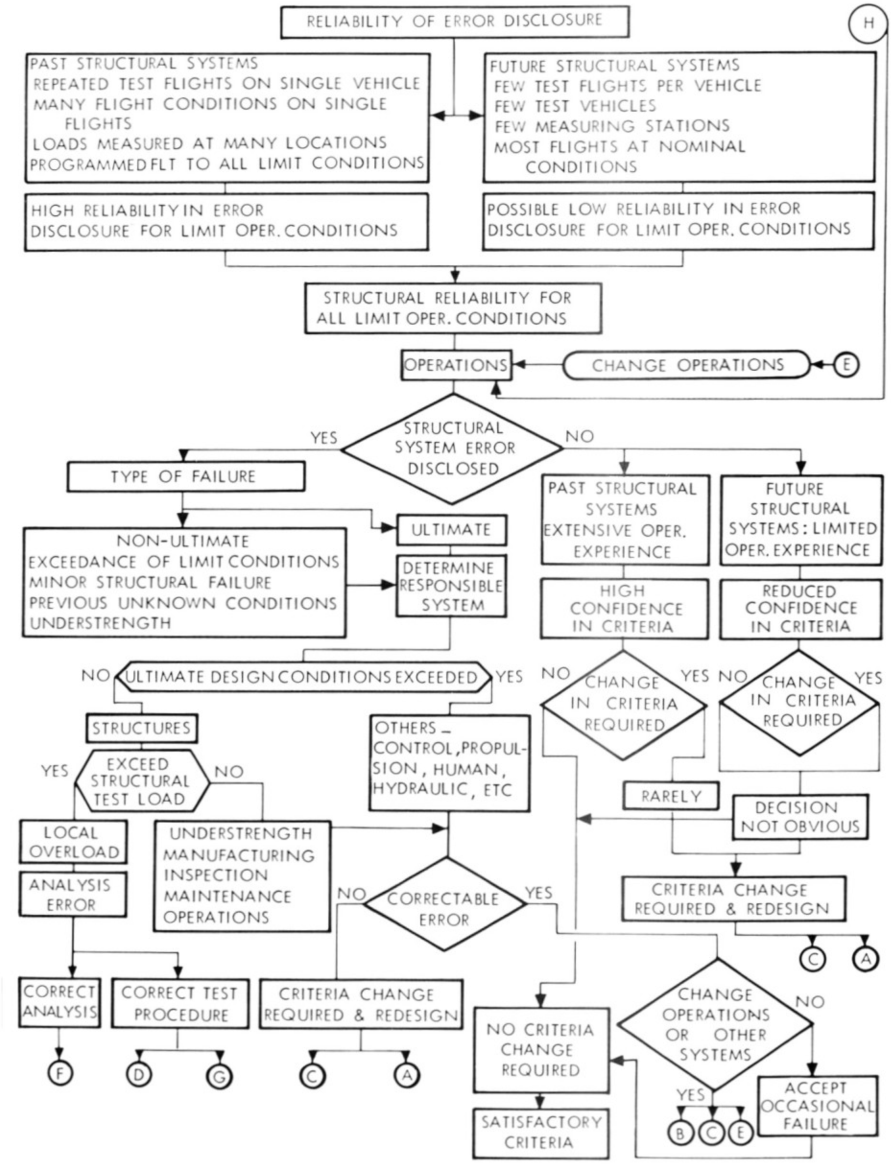

Figure 8. Structural design criteria ingredients.

In the past the ultimate condition was not specified directly. As shown in Fig. 6, a relationship with the limit condition was established indirectly by the ultimate factor of safety defining an ultimate load. It is proposed in this paper that all structural design criteria be defined in terms of separate limit and ultimate conditions, not related by a specific factor of safety. It is further proposed that desired values for structural reliability be established for both limit and ultimate conditions.

Limit or Expected Conditions: The definition of limit or expected conditions is more a question of executive decision than one of statistics. If the designer and operator of a vehicle system agree that a condition is permissible, that condition *is* an expected condition, regardless of whether every vehicle or only 1 in 1,000 encounters the condition. It is the function of structural design criteria to require formulation of explicit procedures which will prevent gross exceedance of operational limitations. If it appears that a limitation is being exceeded "too often," appropriate action must be taken.

As an example of defining limit conditions by executive decision, consider how the expected landing condition might be defined in the case of a multiple-parachute recovery system for a spacecraft. Statistics on the landing-impact velocity might be available, gathered from extensive drop tests and even from actual operations. However, it is more likely that the landing condition would be defined in terms of impact velocity with one parachute failing to deploy. If the executive decision had been to design for the impact velocity with all the parachutes deployed, there would also have to be a decision to revise the recovery system rather than the structure if failure ever occurred as a result of a hard landing with one parachute undeployed.

Most spacecraft and booster systems are being designed for limit winds and wind shears corresponding to those exceeded only one percent of the time. If launch control management action restricts actual launches to much less severe conditions, the limit condition should be reduced accordingly. While statistics of the atmosphere determine the frequency with which operating limitations restrict operations, they do not determine structural reliability. The statistic of true concern for reliability is the probability of encountering an atmospheric condition more severe than the operating limitation when the launch controller had predicted a less severe condition. Definition of the limit condition in terms of the wind and wind-shear environment modified by launch control management is analogous to the traditional definition of aircraft limit gust velocity on the basis of a certain amount of gust avoidance.

Ultimate or Unexpected Conditions: Ultimate conditions should be established separately and without a fixed relationship to limit conditions.

Some might be five percent beyond corresponding limit conditions and some 500 percent beyond. In any event, the ultimate condition should be so defined that any exceedance of the ultimate should obviously result from a gross discrepancy in some system other than the structural. The function of an ultimate condition is to define a rare or unexpected vehicle condition that most vehicles should survive and beyond which most can be expected to fail.

Structural Reliability for Limit Conditions: With the basis for limit and ultimate conditions established for criteria purposes, the level of structural reliability required for each condition must now be defined. Failure at a limit condition is not expected and should be rare. It is suggested that the failure probability at limit conditions should be no more than one percent of the total probability of failure. This would establish a maximum permissible lifetime unreliability at limit conditions varying from 10^{-4} to 10^{-9} for high- and low-risk vehicles, respectively. Such extremely low values cannot be determined by the techniques of classical statistics because of insufficient data.

Since a completely probabilistic approach is not feasible, it is proposed that current criteria be based on a semiprobabilistic approach. As a specific example, a limit factor of safety would be established. While similar to the present factor of safety, this limit factor would differ in purpose. Its sole purpose would be to provide a high reliability against failure at the limit condition or less. The limit factor of safety would have no function in providing a margin for violation of the operating limits.

For structural systems comparable to those of the past, the definition of limit factor of safety is relatively easy. It would take the form illustrated in Fig. 9. This shows the limit factor that would be necessary with a 99-percent exceed allowable and strength variance as defined by γ. The upper curve would define a failure rate of 1 in one billion at limit conditions and the lower curve, a failure rate of 1 in ten thousand. It is interesting to note that the usual F.S. of 1.5 is more than adequate to provide extremely high reliability for all γ's less than 0.075, which corresponds approximately to the upper limit of good aerospace material.

In many of the new problem areas, the modified factor-of-safety approach will not be adequate. This is particularly true of areas where there is no simple load-strength relationship (e.g., fatigue, creep, ablation, and particle-erosion situations). Here consideration must be given to the exact mechanism by which high reliability can be achieved at limit conditions. In fatigue, it is believed that the emphasis in the past has been directed to the wrong phenomena. If a structure is known to encounter a particular loading spectrum, the determination of the mean life under that loading condition is not the significant parameter. The expected life must be a small fraction of the mean life to ensure high fatigue reliability. High reliability is not necessarily provided by testing to failure. It appears that the significant function in fatigue analysis is residual strength [12]. Particularly vital is the variance in residual strength, but very little is known of the scatter in fatigue residual strength at small fractions of the mean life.

In the case of ablative materials, a particular structure may survive an extreme or ultimate temperature of 5000°F with a reliability of 1 in 100. At the normal or expected temperature of 3000°F, very high reliability may result automatically—or it may be only slightly higher than the ultimate reliability. There simply is no fixed relationship. At 3000°F, hot spots may form in the char and erode away almost as fast as at 5000°F. Recognition of the fact that reliability at some extreme condition will not necessarily provide high reliability at some nominal condition is an essential first step in developing techniques to meet the need.

Structural Reliability for Ultimate Conditions: As previously stated, most vehicles should survive ultimate conditions. "Most" represents a relatively finite term that has been quantified as 99 percent in many past situations. This is a conditional reliability that can be calculated meaningfully following a reasonable number of structural tests on components and full-scale structures. A conditional reliability approaching 0.99 is automatically attained if the material allowable represents a 99-percent-

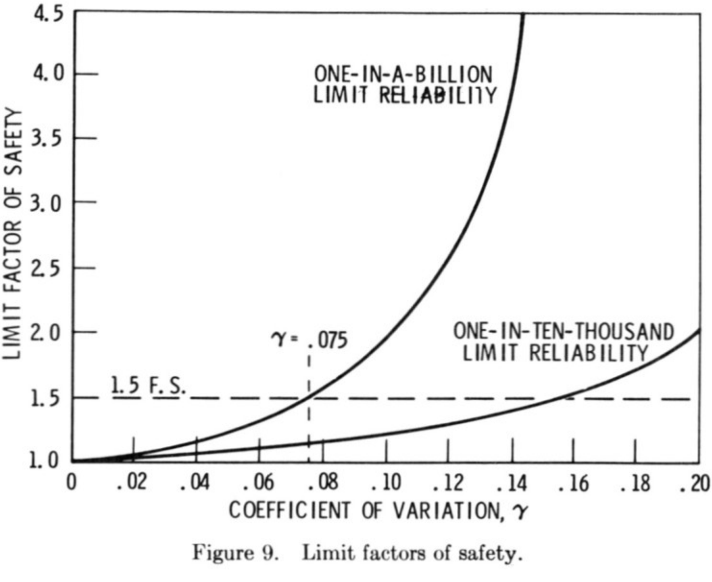

Figure 9. Limit factors of safety.

exceed value and if the structural analysis is correct. Then the total P_F will be equal to or less than the P_E of the ultimate condition. If the P_E of the ultimate condition is the same order of magnitude as the acceptable unreliability, no ultimate F.S. is required to attain the desired level of structural reliability.

The desired reliability at ultimate condition is not necessarily provided by application of a factor of safety to the limit loads. For example, a very nonlinear situation may develop in some lifting entry vehicles, as shown in Fig. 10. At the critical entry velocity, both the load and strength may vary with the load factor. In such a situation, acceptable reliability at the ultimate condition would not be attained since most of the structures would fail at a condition only 120 percent over the limit condition.

Structural Design Analysis. The next major element in establishing satisfactory criteria is shown in Fig. 7. This is the capability to perform accurate structural design analysis. The calculation of loads and other structural parameters, such as temperature, acceleration, and particle-impingement velocity, is a vital part of the structural reliability picture. Since nothing fundamentally new in loads and strength analysis is proposed here, the subject will not be discussed further.

Structural Testing. As shown in Fig. 7, structural testing and the reliability with which errors in the structural system are disclosed are the next major ingredients for achieving structural reliability. It does not appear that the function of structural testing in providing high structural

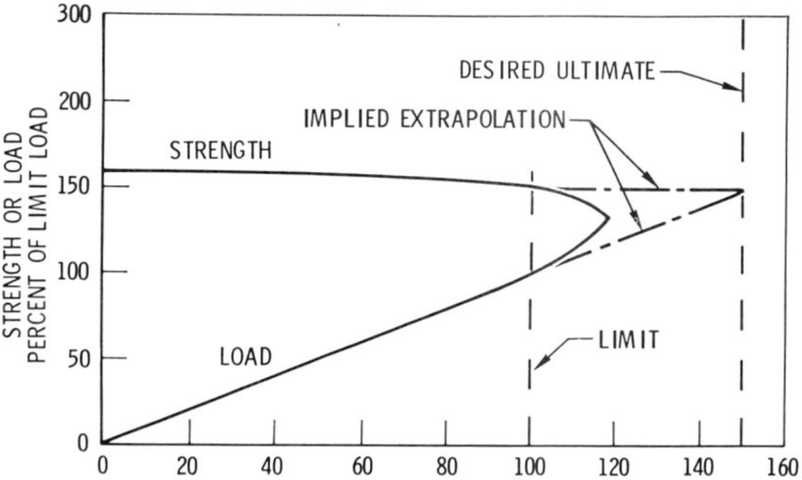

Figure 10. Non-linearity in structural system.

reliability has been fully appreciated in the past. Jablecki [13] has portrayed a rather pessimistic picture of the reliability associated with analysis alone. He analyzed the failures experienced during aircraft structural testing at Wright-Patterson Air Force Base from 1940 through 1949. His failure expectancy curve for wings is reproduced in Fig. 11. Since about 13 percent of the wings did not sustain limit load and about one percent failed at 40 percent of ultimate, strength analysis alone cannot be considered to provide the desired reliability. Those who predict reliability without considering the probability of analytical errors and the capability of physical testing to disclose these errors are guilty of an improper use of statistics.

The way in which structural testing fulfills the error-disclosing requirement can be discussed in terms of the system represented by Fig. 1. It has been established that the limit unreliability is 10^{-50} if—and only if—the strength is as calculated. Jablecki's data show that the true analytical unreliability at limit is approximately 10^{-1}. If the structure undergoing

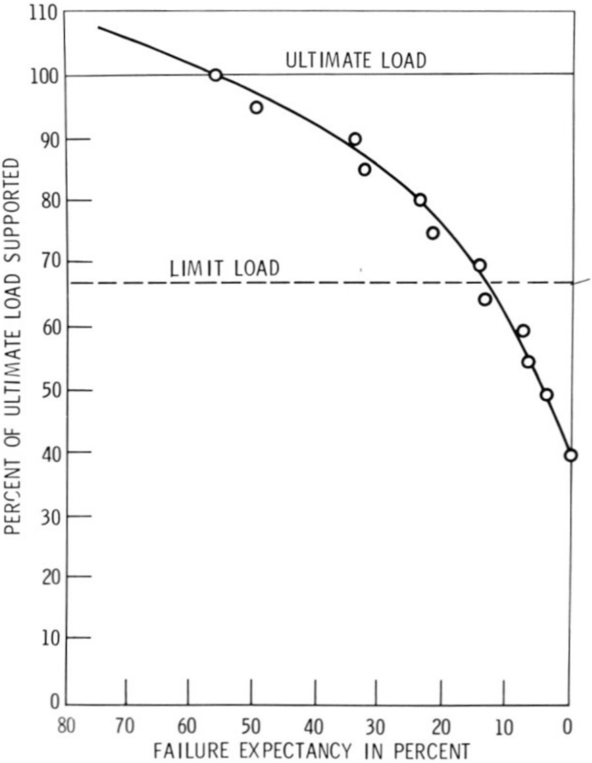

Figure 11. Failure expectancy in structural testing.

test has a real strength of two-thirds the expected value, the strength picture would appear as shown in Fig. 12. The probability of the structure sustaining ultimate load without failing and disclosing the error is 10^{-60}. On this basis, a structure that has been successfully static-tested is a very reliable structure for limit conditions.

If the structural system does not possess the small variance assumed in the previous discussion, the limit reliability due to a single test deteriorates rapidly (Fig. 13). When $\gamma = 0.25$, the limit P_F of the system, even after a successful static test, is higher than 10^{-1}. A single static test does not contribute much to the limit reliability of this type of system. (It is beyond the scope of this paper to define exactly how to handle the problem of structural reliability from testing, but the problem requires extensive future study.)

Fatigue tests are not as effective in disclosing errors affecting structural reliability as are static tests. Tests of fatigue conditions that represent the expected fatigue environment are not explicitly designed to disclose whether the limit reliability is at the level desired. A rigorous confirmation of limit reliability would require a fatigue test to the limit spectrum, followed by a static test to ultimate. Because residual strength in fatigue does not have the small variance typical of the ultimate strength, repeat tests may be

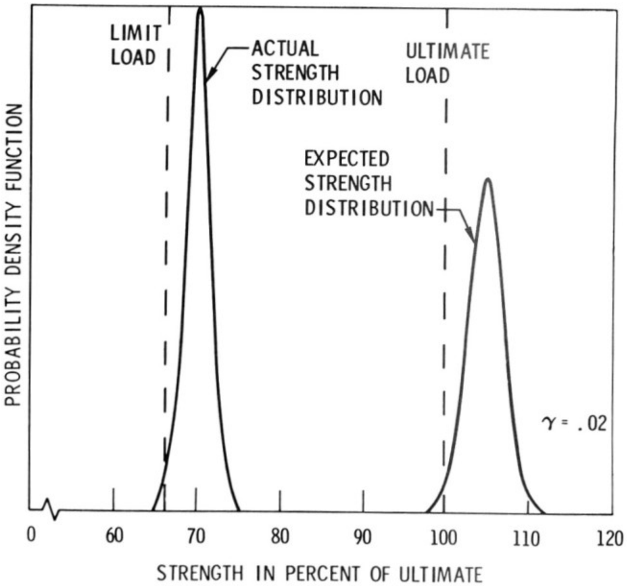

Figure 12. Strength distribution with error in analysis.

required to demonstrate limit reliability. A second series of tests would be required to separately confirm ultimate reliability. The ultimate spectrum would be applied to the structure, followed by static test to limit conditions. Lack of tests designed to disclose true reliability levels in structural systems may have been responsible for many of the fatigue difficulties of recent years.

Loads Testing. After successful completion of the structural tests, the structure as now constituted should have a high reliability for the test contions. These test conditions may or may not correspond to the real environmental conditions. Therefore, as shown in Figs. 7 and 8, loads testing is required to disclose errors in the loads analysis. If all the limit conditions cannot be attained during the loads testing program, statistics on analytical accuracy, comparable to Jablecki's strength-analysis statistics, must be developed and incorporated into a more conservative initial definition of limit and ultimate conditions.

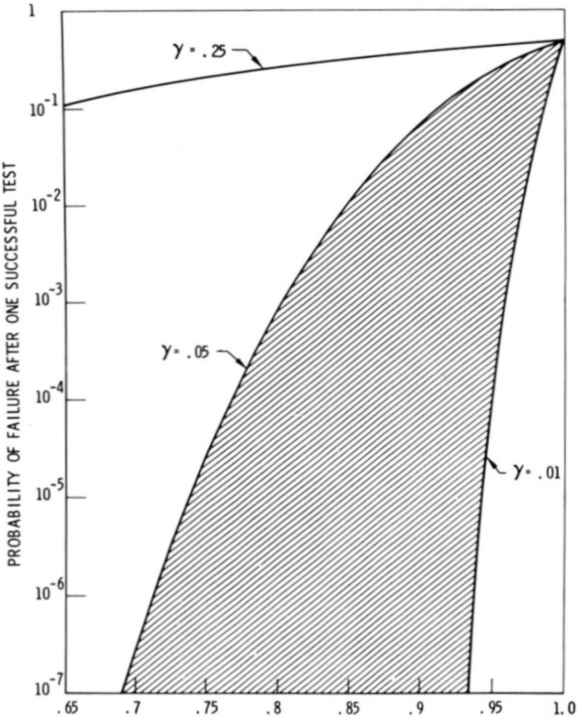

Figure 13. Effect of strength variance on limit reliability.

Operational Disclosure of Errors. If all errors in the structural system, as disclosed by structural and flight testing, have been corrected, the structure is very reliable for the conditions tested; as yet, however, it is not necessarily a reliable system. Operations with the system may disclose additional errors. As shown near the bottom-center of Fig. 8, it may be established that the structure was at the required specification strength when a failure occurred. In this case, other systems must be responsible for the overload. A decision must be made as to whether the error can be corrected. If it cannot be corrected, the structural design criteria must be changed so that the structure will tolerate the error. If the error can be corrected, a decision must be made as to whether the operational correction is feasible and more acceptable than the penalties associated with not changing the operations involved. This choice of solutions to correct an error revealed by a failure is equivalent to choosing between modifying the statistics of the structural system or of the operating procedures, or accepting the failure rate associated with the particular error.

On the other hand, the structural system may be at fault, failing because either the internal structural loads were higher than determined by analysis and test or the structure was understrength relative to the structure tested. In both cases, the error must be corrected because the criteria do not make any provision for gross errors.

NONULTIMATE FAILURES AS ERROR DISCLOSERS

In this final paragraph is presented one of the major factors which have enabled past structural design criteria to produce satisfactorily reliable vehicles. It is well known that many minor, nonultimate failures have occurred in the past at flight conditions far less severe than ultimate. These nonultimate failures disclose errors in the system in the same fashion as do ultimate failures but without the catastrophic consequences. Most of these minor failures stemmed from yielding failures in ductile material. Since most yield strengths have been in the range of 70 to 80 percent of the ultimate, they will be encountered hundreds or thousands of times more frequently than ultimate. Therefore, a yield failure will be far more likely than an ultimate failure in this type of system. If the new structural systems do not have a nonultimate failure-disclosing capability, a specific increment in reliability will be needed to compensate for the degradation.

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COMMENTARY

A. VAN DER NEUT (*Technical University, Delft, Netherlands*): Every now and then a prophet stands up arguing that a factored limit load is inadequate to provide for strength and that a physically realistic load condition has to be devised, the ultimate load, representing the extreme load condition which the structure should be able to sustain before failure. I myself have been among these prophets; I might recall my AGARD report. Now, the difficulty is how to use the ultimate load concept. With unmanned vehicles, where you possibly can tolerate a large rate of failure, you may have sufficient statistical data to establish from it the ultimate load warranting a required probability of survival. However, with manned vehicles the tolerable rate of failure is so extremely small that you will never have the statistical data necessary for defining the ultimate load.

One can think of an indirect method to estimate the ultimate load based upon the use of past experience: translating the available strength of vehicles which gave satisfactory experience into ultimate load conditions, which then are conservative substitutes for the required ultimate load. These ultimate load conditions could then be applied to the design of new vehicles. My question is whether Mr. Bouton knows of other and better methods to effectuate the ultimate load concept.

REPLY

Hopefully, the future will show that I am a prophet as Prof. van der Neut suggests. First, let me clarify that I do not believe that a factored limit load is inadequate; only that an invariant factor is inadequate. Past efforts to be more rational in defining ultimate loads have foundered because they did not satisfy the following requirements: (1) definition of a limit condition representing the upper bound of normal operation; (2) an ultimate strength level far enough beyond this limit condition so that the structure will "never" fail at the limit condition; and (3) a strength level high enough to tolerate operations so far beyond the limit condition that they constitute gross error in operation. Present procedures have generally satisfied these requirements by indirection. To explicitly satisfy them, we must think in terms of two different ultimate loads. The first is defined by the limit F.S. of Fig. 9 and provides very high reliability at limit conditions. This limit F.S. is purely a structural function. The second ultimate load provides the required overload capability so that the ultimate condition will be rarely exceeded. The ultimate F.S. providing this capability is a completely different parameter than the limit F.S. and must be based on purely operational considerations. Even without appropriate statistics, a judgment decision can define an ultimate condition such that the increment from the limits to the ultimate condition represents a gross error in operation. Such a gross error can be reliably prevented so the structure need not tolerate operations beyond that level. This qualitative definition of an ultimate condition is valid whether the vehicle is manned or unmanned. The ultimate F.S. might be different for each different operational mode and each class of vehicle.