Vulnerability Assessment and Ranking of Steel Bridges

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Failure of Connecticut's Mianus River bridge in 1983, the New York State Thruway's bridge over the Schoharie Creek in 1987 and the recent failure of the US 51 bridge in Covington, Tennessee, have underscored the importance of inspection, evaluation and maintenance in achieving bridge safety. However the magnitude and cost of arbitrary bridge safety assurance actions can be prohibitive. Since budgetary restraints limit even safety actions a prioritizing system is needed which can identify the most vulnerable bridges for remedial project work. The system must distinguish between rather benign local failures and catastrophic failures resulting in a significant hazard to the lives of the travelling public which may include total collapse of a bridge or bridge span. This paper presents the essential details of such a system which provides a practical and immediately implementable method of identifying the most vulnerable bridges or spans within a given population. It is being reviewed for inclusion in a comprehensive bridge management program currently being implemented by the New York State Department of Transportation.

Reference 1 presents a probabilistic model for the vulnerability assessment and ranking of steel highway bridges or bridge spans and discusses some practical applications. Vulnerability ranking is a means of prioritizing the repair, retrofit, rehabilitation, and replacement of in-service bridges. In order to perform vulnerability ranking of a group of bridges or spans, the degree of vulnerability of each bridge or span in the group must first be determined. This process is vulnerability assessment. The term "bridge" will refer to either a complete bridge or an individual span.

Vulnerability assessment and ranking is being reviewed for inclusion in a comprehensive bridge management program currently being implemented by the New York State Department of Transportation (NYSDOT). As part of that program, the procedures described herein were developed and proposed by the NYSDOT Bridge Safety Assurance Task Force (BSATF), an independent committee formed to review New York State's safety assurance measures (2, 3).

DEFINITION OF VULNERABILITY

The model is based on fundamental structural reliability and risk assessment concepts, both of which are applications of the mathematical theory of probability. Because probabilistic methods attempt to deal rationally with uncertainty, they are well suited to studies of bridge safety. Vulnerability is the relative probability that a given bridge will fail within a given period of time, say, the next two years. The two year time period is practical because it corresponds to the federally-mandated inspection interval. The term "relative probability" is a quantitative measure of the relative likelihood of an event, defined on an arbitrary numerical scale. To rank a group of bridges according to their vulnerability, the "true" failure probability for a given bridge is not needed; rather it is only necessary to know whether a given bridge is more or less likely to fail than the other bridges in the group.

In the vulnerability assessment model, relative failure probabilities are, for the most part, subjectively defined. Use of subjective probabilities as the basis for engineering decision-making has been well established in basic Bayesian Decision Theory (4).

In the definition of vulnerability, "failure" is any major change in the geometry of the bridge which creates a significant hazard to the lives of the traveling public. This definition is a direct reflection of New York State bridge management program's emphasis on public safety. Note that, as used here, the term "failure" encompasses a wide range of limit states. For the purpose of vulnerability assessment, a bridge has "failed" if, for example:

- The entire bridge has collapsed.
- One or more spans have collapsed.
- The floor system fails, resulting in severe injury or loss of life.
- Failure of a main member (e.g. girder fracture) causes large deck deformations which result in severe injury or loss of life.

Note that the model is designed to ignore rather benign local failures and to identify potential catastrophic failures.

THE VULNERABILITY ASSESSMENT MODEL

Formulation of the vulnerability assessment model is accomplished in four steps, as follows:

(1) Six significant failure modes are identified for steel bridges. These are based primarily on the observed performance of in-service bridges (5). Types of failure observed most often are considered to be the most significant.

(2) Each failure mode is analyzed to determine specific structural characteristics, conditions, and events which might

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contribute to the failure.
(3) These characteristics, conditions, and events are incorporated into a single logic network, called the Vulnerability Assessment Flowchart. The flowchart, which is shown in Figure 1, is designed to generate a quantitative vulnerability assessment for a given bridge. To achieve a vulnerability assessment, the flowchart guides the user through a series of decision points, the outcomes of which depend on the general characteristics and condition of the bridge being assessed.
(4) Specific guidelines for the use of the flowchart are prepared. These guidelines provide standard criteria for selection of outcomes at decision points.

Definitions

The formulation of the vulnerability assessment model includes a number of key terms. They are as follows:

MEMBER - A major structural element requiring separate design consideration; e.g., girder, floor beam, stringer.
COMPONENT - A discrete part of a member; e.g., flange plate, web plate, flange angle (in a riveted plate girder).
INTERNAL REDUNDANCY - Capacity of a member to carry load following the fracture of a single component of that member. Riveted plate girders and multiple eyebar truss members have a high degree of internal redundancy (6). Welded plate girders and rolled sections have no internal redundancy.
STRUCTURAL REDUNDANCY - Capacity of a structure to carry load following the fracture of a single member. Multi-girder bridges have high structural redundancy (7). The structural redundancy of two- and three-girder bridges can range from low to moderate, depending on the configuration of their secondary or redundant bracing systems (8).
DETECTABLE DECK DEFORMATION - After-fracture deformation of the bridge deck which is clearly noticeable to occupants of crossing vehicles, but is not large enough to constitute a significant safety hazard. If detectable deck deformation occurs following a member fracture, traffic is likely to be quickly halted. If detectable deck deformations do not occur after a fracture, traffic will continue to cross the bridge, and the intact portion of the structure will continue to accumulate fatigue damage; and the likelihood of catastrophic failure will increase. For example, detectable deck deformation did not occur after near full depth fracture of the girder of the I79 and Lafayette St. bridges (9).
FATIGUE RESISTANCE - Characteristics of structural members, components and connections which affect its susceptibility to fatigue cracking (9). These characteristics include design details and workmanship.
MATERIAL TOUGHNESS - Capacity of a metallic material to resist fracture.
ADTT - Average Daily Truck Traffic for a given bridge.
WATER CONTROL - Existence of well-maintained expansion joints, drains, and gutters, which carry water and dissolved salts off of the deck surface without allowing contact with the steel superstructure.

Significant Failure Modes

As shown in Figure 1, six significant failure modes are identified for steel bridges. They are as follows:

- Failure Model 1: Fatigue cracking occurs in primary members, such as plate-girders, tie-girders, floor beams, truss members or their connections. Cracking may lead to brittle fracture.
- Failure Mode 2: Collision of a vehicle or vessel with a member causing loss of load-carrying capacity.
- Failure Mode 3: Fatigue cracking in hangers, pins, or seats of a suspended span. Cracking may lead to brittle fracture.
- Failure Mode 4: Hangers supporting a suspended span fail due to "pack out" of retainers on the hanger pins (Mianus).
- Failure Mode 5: Fatigue cracking occurs in a steel pier cap or other steel substructure member(s).
- Failure Model 6: Corrosion of primary members causes loss of load-carrying capacity.

Although these failure modes are not all inclusive, they are applicable to short-and medium-span bridges (with or without floor systems) and to the floor systems of long-span bridges. They are not fully applicable to the main load-carrying members (truss members, arch ribs, or cables) of long-span structures. This is because Failure Modes 1, 3, and 5 are primarily concerned with fatigue effects caused by vehicular loading. These effects are quite significant for short- and medium-span bridges and for the floor systems of long-span bridges. For the main load-carrying members of long-span structures, however, the dead load-to-live load ratio is so large that fatigue effects are rarely significant. Vulnerability of these members is expected to be governed by other failure modes which are beyond the scope of this paper.

Vulnerability Assessment Flowchart

The Vulnerability Assessment Flowchart shown in Figure 1 is organized such that the six failure modes are considered in sequence. A vulnerability assessment must consider all six failure modes.

The purpose of the Vulnerability Assessment Flowchart is to determine a relative probability of failure for a given bridge, based on its general characteristics and current condition. The formulation of the flowchart consists of two distinct elements: the logic network and the relative failure probabilities.

LOGIC NETWORK

The logic network follows directly from a "fault tree" analysis which is described in Reference 1. Referring to Figure 1 the network consists of a series of decision points, which are designated with diamond-shaped boxes. For reference, each decision point is labeled with a letter in parentheses; e.g., (a). Each decision point has two or three possible outcomes. Selection of the appropriate outcome at each decision point depends on the general characteristics and condition of the bridge being assessed. Decision points are interconnected with

(a) Failure Mode 1

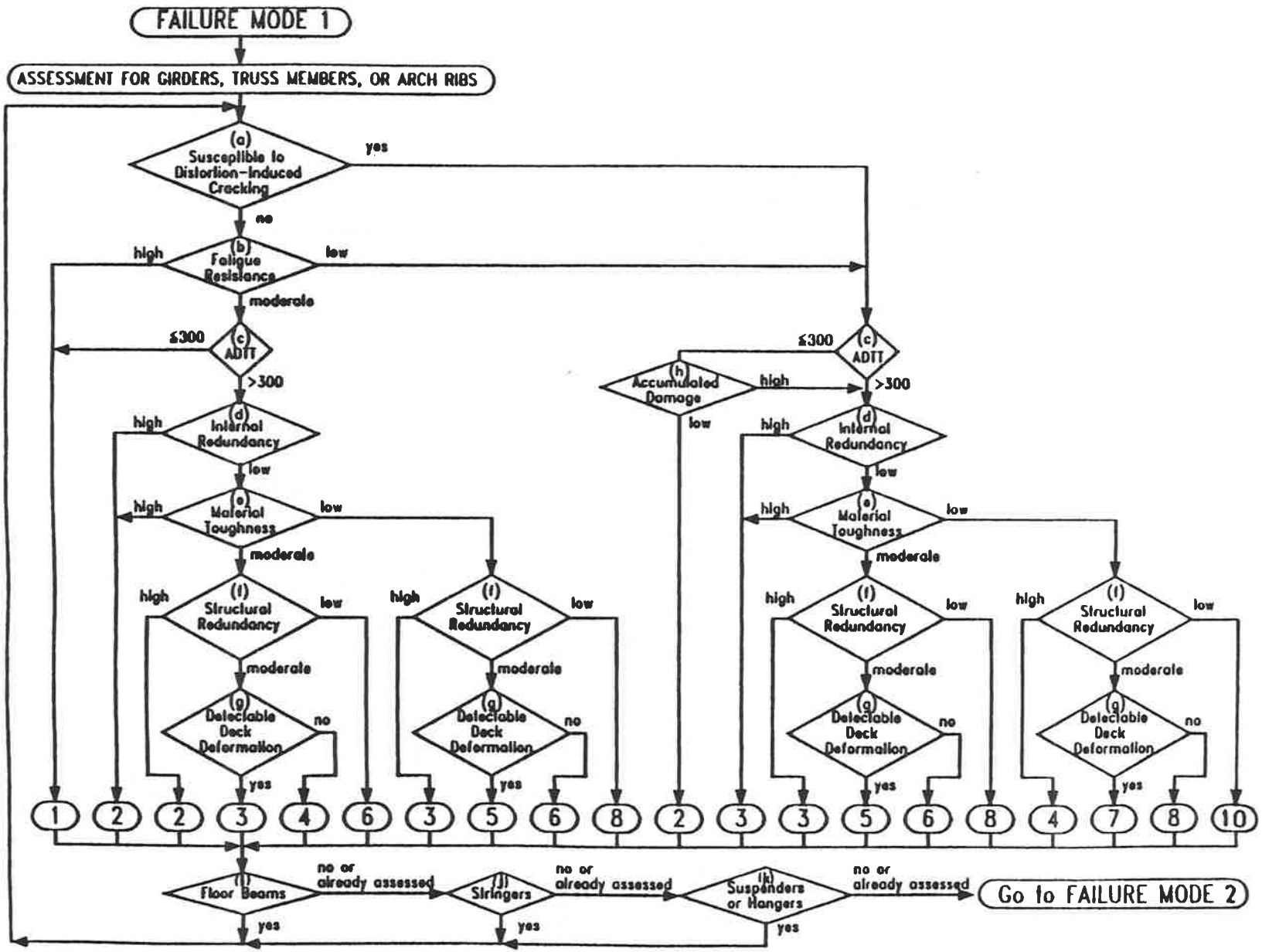

Figure 1. Vulnerability Assessment Flowchart

(b) **Failure Modes 2, 3, and 4**

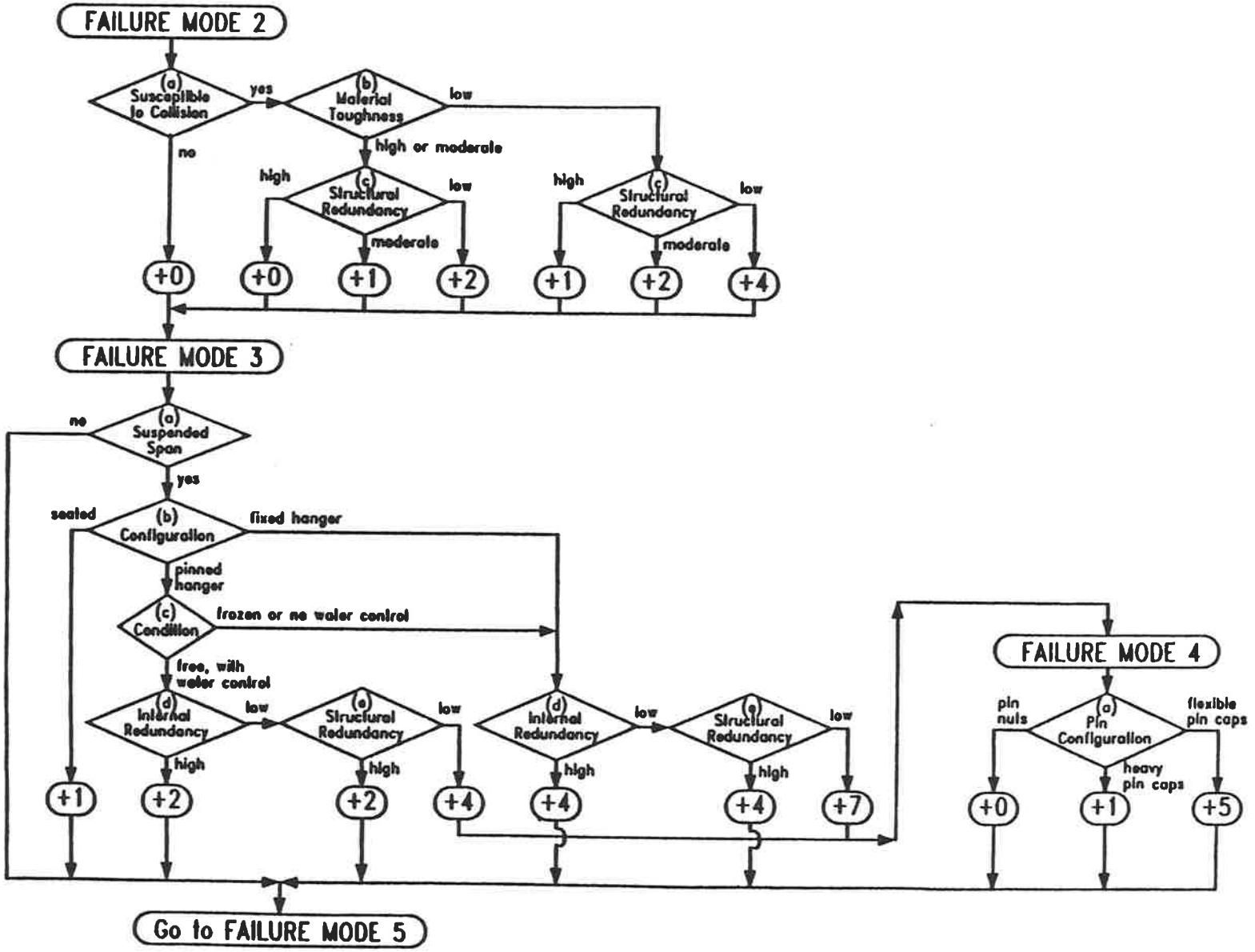

Figure 1. Vulnerability Assessment Flowchart (Continued)

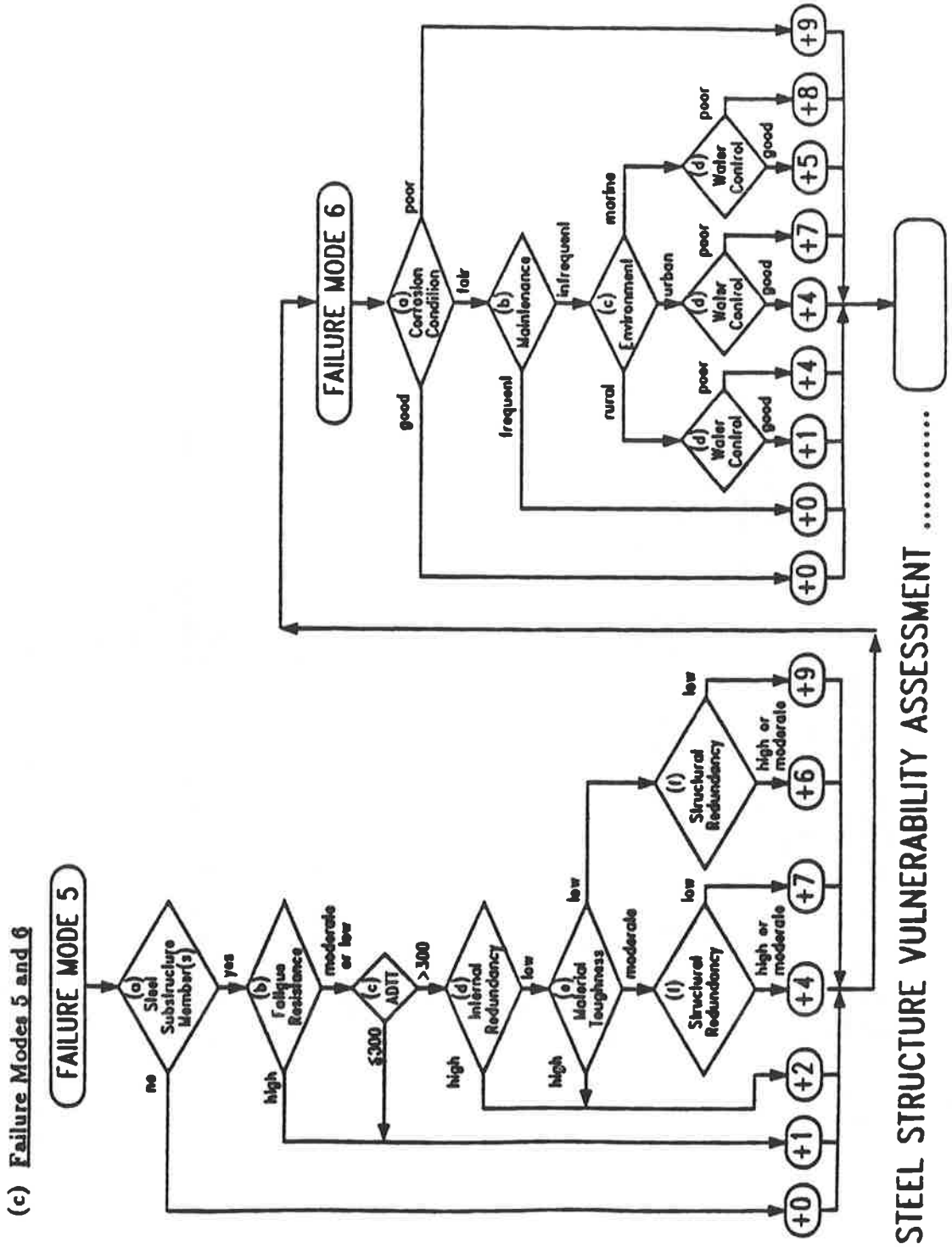

Figure 1. Vulnerability Assessment Flowchart (Continued)

lines, to form the logic network. Arrowheads are placed on the lines to show the direction of logical flow. Each possible path through the network yields a relative failure probability for each failure mode. The relative probabilities are contained in small ovals. The **TOTAL VULNERABILITY ASSESSMENT** (Figure 1(c)) is the sum of the six failure mode probabilities.

The logic network for Failure Mode 1, Figure 1(a), also contains a "loop" - a path which returns the user to the first decision point for certain types of bridges. The loop dictates that the vulnerability assessment for Failure Mode 1 must be performed more than once for any bridge which has floor beams, stringers, suspenders and/or hangers. Note that the vulnerability assessment for Failure Mode 1 may be performed as many as four times. The assessments for all passes through flowchart must be added together to obtain the total relative failure probability for Failure Mode 1. Thus the vulnerability assessment for Failure Mode 1 can take on any value from 1 to 40.

The loop in Failure Mode 1 is used because bridges with floor beams, stringers, suspenders, and/or hangers have additional significant failure modes. On a given bridge, main load-carrying members, floor beams, stringers, and hangers generally have very different characteristics. They are likely to have different susceptibilities to distortion-induced cracking, different fatigue resistances, and different degrees of internal and structural redundancy. They are also subject to different numbers of load cycles and somewhat different magnitudes of live load. Though the total vulnerability assessment for Failure Mode 1 can potentially be as high as 40, it is highly unlikely that the total will exceed 25 for an actual bridge. The reason is that floor beams, stringers, suspenders and/or hangers tend to have high or moderate structural redundancy. If one of these members fractures, numerous alternate load paths generally exist. Thus the individual vulnerability assessments of these three types of members will rarely, if ever, exceed 5 each, for a total of 15, which when added to the 10 from the first loop gives and overall total of 25.

It is acknowledged that fracture or fatigue failure of, say, a floor beam is not likely to be as serious as fracture of a main girder. A floor beam fracture may only result in a local deck failure, while a main girder fracture might well result in collapse of the structure. Note, however, that the definition of failure used in this paper does not discriminate between local failure and catastrophic failure. The significant point is that if a floor beam failure and a main member failure both constitute a "hazard to the traveling public", then they are, in effect, equally weighted failures, and the local failure is not a benign failure in this case.

RELATIVE FAILURE PROBABILITIES

The relative failure probabilities shown in the small ovals on the Vulnerability Assessment Flowchart are defined via a simple "calibration" process. Based on the observed frequency of distress in in-service steel bridges, Failure Model 1 is judged to be the predominant failure mode. For this reason, the maximum possible failure probability for Failure Mode 1 is used to calibrate the remainder of this flowchart. The maximum value for one pass through the Failure Mode 1 network is arbitrarily assigned a value of 10, and all other numbers in the flowchart are defined with respect to that value. For example, a value of 5 indicates that the corresponding path through the flowchart represents a probability of failure which is one-half that of the worst-case path for Failure Mode 1.

The total vulnerability assessment for all six Failure Modes can potentially take on any value from 1 to 74. The maximum value of 74 has no particular significance, since it is a relative probability. Experience using Figure 1 for vulnerability assessments of actual bridges indicates that the total vulnerability assessment will rarely exceed about 40 or 50 (2,3).

Though the relative failure probabilities indicated in the flowchart have been developed rationally, they are primarily the product of the experience and judgement of the authors and NYSDOT engineers. As such, they are subject to modification, based on future experience and observations of distress in steel bridges.

LEVEL OF SIMPLIFICATION

A deliberate attempt has been made to keep the flow chart as simple as possible. This is accomplished in two ways: (1) Only those decision points which are considered to have a significant influence on bridge vulnerability are included. (2) No more than three outcomes are defined for each decision point.

This level of simplification is judged to be appropriate, given the nature and intended use of the flowchart. It has been found that the addition of decision points or outcomes tends to cause a disproportionately large increase in the complexity of the logic network. As the logic network becomes more complex, subjective calibration of the relative likelihoods of failure becomes considerably more difficult. Large increases in complexity also render the flowchart too unwieldy for manual use.

Given that the Vulnerability Assessment Flowchart is simply a logical algorithm, it can be easily converted to a computer program or for use with an expert system. Such a program would not necessarily be constrained to any particular level of simplicity.

GUIDELINES FOR USE OF THE VULNERABILITY ASSESSMENT FLOWCHART

In order to ensure that vulnerability assessment is performed in a consistent manner, it is necessary to establish guidelines for selection of each possible outcome at each decision point in the Vulnerability Assessment Flowchart. A recommended set of decision criteria has been developed and is included in References 1, 2 and 3.

These guidelines are very specific in nature. As an example, consider the first two decision points in **FAILURE MODE 1**. Decision Point (a) is an assessment of "Susceptibility to Distortion-Induced Cracking". The guidelines specify that this decision point is to be answered with "yes" if any one of the following conditions exist:

- Narrow web gaps exist at transverse stiffeners, floor beam connection plates, or diaphragm connection plates. For

example, webs are susceptible to out-of-plane bending (9).

- Cantilever brackets or outriggers have tie plates which are connected to girder flanges. Tie plates are susceptible to high inplane bending stresses (9).
- Floor beams or stringers are coped. (Coped webs are susceptible to high bending stresses caused by excessive restraint at connection (9).

As another example the guidelines specify that Decision Point (b), "Fatigue Resistance", is to be answered with "low" if any of the following are true:

- One or more primary members are flagged because of known fatigue cracks.
- One or more primary members have large fabrication defects of poor welding workmanship, as evidenced by visual inspection; e.g., lack of fusion or cold cracking.
- Primary members have category E or E' details.
- Tack welds, plug welds, or other non-standard welds are present.

The complete guidelines establish similar criteria for selection of outcomes at all decision points in the flowchart which is shown in Figure 1.

APPLICATION OF THE VULNERABILITY ASSESSMENT MODEL

The vulnerability assessment model described above is applicable to a wide range of structural configurations, to include deck-girder, through-girder, box-girder, truss, and tied-arch bridges.

The model can be used to assess simply-supported spans, continuous spans, and suspended-span configurations. It is applicable to bridges with short and medium span lengths and to the floor systems of long-span structures.

Though the vulnerability assessment model has been developed principally for use by NYSDOT, its applicability is by no means limited to New York State bridges. The logic network of the flowchart is expected to be fully applicable to steel bridges in other states. The relative probabilities and guidelines may require minor modifications, based on local experience. For example, in those southern states where salt is not applied to roads in the winter, corrosion may be less significant and thus may warrant lower relative probabilities for Failure Mode 6. Similarly, the guidelines may require modification or augmentation as a result of differences in local design and inspection codes.

EXAMPLE VULNERABILITY ASSESSMENTS

As part of the development of the vulnerability assessment model, example vulnerability assessments have been performed for seven in-service bridges. Of these, six are New York State bridges. The seventh is the I-95 Bridge over the Mianus River near Greenwich, Connecticut, which failed catastrophically in 1983.

The results of these example vulnerability assessments are summarized in Table 1. The seven subject bridges are identified in column (a); a general description of each is provided in columns (b) through (h), and the corresponding vulnerability assessment is indicated in column (i). Bridges are ranked in order of decreasing vulnerability. The detailed information required for vulnerability assessments of the New York State bridges was readily available from NYSDOT's bridge inspection (BIN) files, construction drawings, and bridge management data base. Information on the I-95 Bridge was obtained from other sources. Step-by-step descriptions of the seven vulnerability assessments, which include the justifications for selection of outcomes at all decision points, are included in References 2 and 3.

In comparing the vulnerability assessments shown in Table 1, several interesting observations can be made:

- It is not surprising that the Mianus River Bridge is assessed as the most vulnerable of the seven bridges considered; however, the characteristics of the bridge which contributed to its collapse (suspended span supported by non-redundant pin-and-hanger assemblies with flexible pin caps) account for only a portion of its vulnerability assessment of 37. The Mianus River Bridge is assessed as highly vulnerable because it has a number of adverse characteristics which independently increase its probability of failure. These include low fatigue resistance of girders, floor beams, and stringers, a non-redundant superstructure configuration, and an adverse combination of fair corrosion condition, infrequent maintenance, and poor water control. The implication is that the pin and hanger detail which failed was only the weakest link in a chain with many weak links.
- Because it is a multi-girder bridge, the Harlem River Drive Viaduct might not be expected to be a highly vulnerable structure. Nonetheless, the vulnerability assessment model assigns it a relatively high vulnerability, primarily because it has a highly nonredundant steel pier cap with poor fatigue resistance.
- The Route 20A and Route 971V Bridges have relatively low vulnerability assessments, despite the fact that they are both two-girder bridges with suspended spans. The reason is that their riveted girders are internally redundant.
- The Route 971V Bridge is somewhat less vulnerable than the Route 20A Bridge because its pin-and-hanger details have been retrofitted with steel rods, to improve their internal redundancy.
- The Ramp from CR 80 is the least vulnerable of the seven subject bridges, for two reasons: First, it is simply configured, with no suspended spans, floor beams, stringers, or steel substructure members. Second, the bridge has a heavy bracing system designed to stiffen its curved girders torsionally; this bracing system greatly improves the structural redundancy of the superstructure.

Note that the relative vulnerability of each bridge is controlled by a different set of contributing factors. Thus these examples serve to illustrate the fundamental concept of the vulnerability assessment model - that no single structural characteristic or condition rating can be used to consistently assess the vulnerability of every bridge. Rather, bridge vulnerability is a function of many contributing factors.

TABLE 1 – SUMMARY OF EXAMPLE VULNERABILITY ASSESSMENTS

a. BRIDGE	b. SUPERSTRUCTURE TYPE	c. SPANS	d. MAIN MEMBERS	e. FLOOR BEAMS	f. STRINGERS	g. HANGERS/ SUSPENDERS	h. SUB STRUCTURE	i. VULNERABILITY ASSESSMENT
1. I-95 Bridge over Mianus River	Deck Girder	3-Anchor 2 Suspended	2 Welded Plate Girders	Welded	Rolled	None	Concrete Piers	37
2. Water Ford Mechanicville Bridge over D & H R.R.	Through Girder	2 Continuous	2 Welded Plate Girders	Rolled w/Welded C.PLs	None	None	Concrete Piers and Abutments	21
3. Harlem River Drive Vidaduct	Deck Girder	Multiple Simply Supported	4 or 5 Rolled Sections with Welded C.PLs	None	None	None	Concrete and Steel Piers	21
4. Robert Moses Causeway Bridge over Great South Bay	Through Truss	2 Anchor 1 Suspended (Tied Arch)	Riveted Truss Box Sections	Welded	Rolled	Riveted Box Sections	Concrete Piers	16
5. Rt. 20A Bridge over Cazenovia Creek	Deck Gider	2 Anchor 1 Suspended	2 Riveted Plate Girders	None	None	None	Concrete Piers and Abutments	11
6. Rt. 971V Bridge over Black River	Deck Girder	2 Anchor 1 Suspended	2 Riveted Plate Girders	Rolled	None	None	Concrete Piers and Abutments	8
7. Ramp from CR 80	Deck Girder	2 Simply Supported	3 Welded Plate Girders (Curved)	None	None	None	Concrete Piers	5

CONCLUSION

Vulnerability assessment and ranking constitute only one step in a comprehensive bridge safety assurance program. They should be followed by more detailed analyses of bridges identified as vulnerable. They should also be supplemented by traditional methods of assessment, such as load and condition rating.

The consequences of failure should also be used to set priorities for bridges having equal or near equal high vulnerability assessments. For example, a bridge in a densely populated area, where detouring of traffic may result in a major disruption of commerce and severe economic impact has a high consequence of failure and should receive higher priority for repair, retrofit or rehabilitation.

Failure modes not included in the model can be considered separately as NYSDOT is currently doing with scour, earthquake, and other failure modes (2, 3). The severity of a given failure mode (within the broad definition of failure) might also serve as a useful "discriminator" in the vulnerability ranking of bridges with approximately equal vulnerability assessments.

The vulnerability assessment model is only a tool - one of many already available to bridge engineers. Its true value is that it fulfills a particular need which cannot be satisfied by any of the existing tools.

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