AMERICAN CONSULTING ENGINEERS COUNCIL'S

AFFILIATE

HEAVY MOVABLE STRUCTURES, INC.

4TH BIENNIAL SYMPOSIUM

NOVEMBER 10TH - 12TH, 1992

SHERATON DESIGN CENTER
FT. LAUDERDALE, FLORIDA

SESSION
WORKSHOP NOTES

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Modjeski & Masters
"Service Life Movable Bridges: 2nd Edition"

SERVICE LIFE OF MOVABLE BRIDGE
THE SECOND EDITION

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ABSTRACT

Little has been published on the reasonable expected service life of movable bridges. For use in apportioning the funding of bridge replacements, the U.S. Coast Guard and the U.S. Army Corps of Engineers have used service lives of 100 years for masonry substructures and 70 years for steel railroad superstructures. These figures came from a statistical study of railroad bridges made by the Interstate Commerce Commission in 1940. Later these same agencies adopted a service life of 50 years for highway bridge superstructures.

In an earlier paper delivered at the 1990 Symposium, the Author showed that the ICC figures were actually the expected average service life of new bridges when new, and that the remaining service life of a movable bridge already in service could differ greatly from the ICC figures.

This paper will report on the results of a nationwide sampling of a large number of movable bridges whose service lives have ended. The actual average service lives developed from this sampling for the different kinds of movable bridges, both highway and railroad, will be presented.

SERVICE LIFE OF MOVABLE BRIDGE
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I. INTRODUCTION

For railroad accounting and depreciation purposes, the Interstate Commerce Commission has designated 70 years as the service life of railroad bridge superstructures, 100 years as the service life of railroad bridge substructures and 37 years for the service life of treated timber in railroad bridges. These values were later adopted and codified by, first the U.S. Army Corps of Engineers, and later the U.S. Coast Guard, in application and administration of the Bridge Alteration Act of 1940, the so-called Truman Hobbs Act. A service life of 50 years was subsequently adopted by the Corps for service life of highway bridge superstructures, when the Truman Hobbs Act was extended to highway bridges in 1952. The service lives are applied without distinction to both fixed and movable bridges.

In an earlier paper delivered at the 1990 Symposium, it was shown that the ICC figures (and by extension, the figures adopted by the USCG and the USCOE for service life) were actually the expected average service life of new bridges when new and that the remaining service life of a movable bridge already in service could differ greatly from the ICC figures. Two methods were introduced in that paper to better estimate the remaining service life of a bridge already in service.

This paper will review those methods for estimating the remaining service life and will present some data on computation of remaining safe fatigue life of key bridge details as another method of estimating the remaining service life of a structure. A hypothetical example of the use of these methods will be shown.

Further, this paper will report on a sampling of a large number of movable bridges, most still in service, but some whose service lives have ended. The actual service lives developed from this sampling for different kinds of movable bridges, both highway and railroad, will be presented.

II. IMPORTANCE OF SERVICE LIFE ESTIMATES

It is important to a bridge owner to have a reasonable, rationally determined estimate of expected future service life of an existing structure. The following instances illustrate the importance of such determination:

- **Pricing of User Fees or Freight Rates**

  The service life of a bridge facility is of importance in the pricing of user fees or, in the case of railroads, freight rates to include adequate depreciation or capital recovery. It was this last that impelled the ICC to develop average service life figures for bridges, and such figures are entirely appropriate for such use.

- **Scheduling of Facility Replacement**

  The remaining service life of a bridge facility is of obvious importance in the scheduling of future capital expenditures for facility replacement.

- **Judicial Determination of Damages in Accident Adjudication**

  The remaining service life of a of the bridge structure usually becomes an issue in the adjudication of damages following a bridge/vessel accident. When the vessel owner claims he owes the bridge owner only for that proportion of replacement cost equal to the proportion of service life remaining, it is in the owner's interest to show that expected remaining service life is large. The difference in damage recovery may be several hundred thousand dollars.

- **Apportionment of Costs in Public Agency Bridge Replacement**

  The apportionment of costs in funding of bridge replacements by the Corps of Engineers and the U.S. Coast Guard requires that the bridge owner bear the cost of the expired service life of the bridge to be replaced. The owner must pay that portion of the capital cost of the old bridge which he has used up, while the public agency funds that portion of the capital cost of the old bridge which has not yet been used, the so-called unexpired service life. In the absence of other data, both the COE and the USCG use the previously adopted service life figures from the ICC Guidelines. Again, however, it is usually in the owner's interest to be able to show that expected remaining service life of the old structure is large, in excess of the amount determined by simple application of the ICC figures. The difference in costs to be borne by the owner may be several hundred thousand dollars.

III. INTERPRETATION OF SERVICE LIFE FIGURES

It is important to recognize that the 70-year and 100-year services lives for steel railroad bridge superstructures and for concrete railroad bridge substructures, are average lives for new facilities. They actually represent the average initial life expectancy when new of a large statistical sampling of bridges; and they are reasonable figures when used for what they are. But they are not reasonable figures when used to determine remaining life expectancy of older bridges. It is not correct to apply the 70-year, 100-year figures to determine the remaining service life of a specific, already existing structure. The simple arithmetic subtraction of existing life from the nominal service life to determine remaining life expectancy, as practiced by some public agencies, is clearly wrong.

When considering the remaining life expectancy of an older structure which may already have existed a large part of, or even more than, the average initial life expectancy as developed by the ICC table, it is intuitively obvious that a simple arithmetic method is fallacious. An analogy to the human condition points up the error. If, at birth a man has a 70 year-life expectancy, then when he has lived 70 years his anticipated remaining life expectancy is not zero, but rather some number of years. If he is still alive at age 80, he still has an anticipated life expectancy of not many, but a few years.

This axiomatic principle has been expressed by Grunsky [1] as follows:

> "Every article which has been in service for some years and has escaped the accidents which might have put it out of business in its early life, stands a better change of being among those which will outlive the probable life term fixed for it when it was new, than it had when new to outlive this term. Consequently the expectancy is not to be determined by subtracting age from probable life. It is to be determined from the actual condition of the article and all local circumstances which may affect its continued usefulness."

IV. ANALYTICAL DETERMINATION OF REMAINING LIFE EXPECTANCY

Our earlier paper, delivered at the 1990 Symposium, showed that remaining life expectancy could be estimated by either the Grunsky Method or the Delair Method. Both methods had greater relevance than the ICC-based figures adopted by the USCG and the COE, and both methods gave similar results.

1. The Grunsky Method - This is a purely mathematical way of determining remaining life expectancy of similar articles (read: bridges) using certain general assumed actuarial principles proposed by Grunsky. The principles are:

- that failures among any large group of articles will be greatest in number at or near the end of probable life term.
- that practically no articles will survive twice the probable life term.
- that there will be a uniform increase in the annual rate of failure from the beginning to the year of maximum number of failures and that the decrease in the number following that year will follow a similar law.

Application of these actuarial principles results in the following:

The Grunsky Formula

Let e = the remaining life expectancy of an article.
m = the present age of the article.
n = the probable life new of the article.

Then when $m < n$

$$e = n - 0.93m + 0.30 \frac{m^2}{n}$$

when $m > n$

$$e = 0.72n - 0.35m$$

As an example:
For the superstructure of Bridge X, built in 1926, where n = 70 year and m = 66 years, the remaining life expectancy by the Grunsky method would be

$$e = 70 - 0.93(66) + 0.30 \frac{66^2}{70}$$

$$e = 27.3 \text{ years}$$

Thus the Grunsky method would predict a total life of 93.3 years for the superstructure, already 66 years old.

The maximum possible life for the superstructure, with a 70-year ICC average service life when new, would be 144 years.

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[1] Grunsky, C. E., Grunsky, C. E. Jr., Valuation, Depreciation and the Rate Base, Second Edition, John Wiley & Son Inc., New York, 1929.

2. The Delair Method - This is a rational method of assessing remaining service life using eight factors which affect the life of any bridge. This method was developed by the Pennsylvania Railroad and their consultants in Truman Hobbs negotiations with the COE for replacement of the Delair Bridge in 1954. It has subsequently been used on other Truman Hobbs bridge replacement projects.

The eight factors and the weights assigned to them in the Delair negotiation are as follows:

		Weight
1.	Deterioration	20
2.	Wear and Fatigue	20
3.	Inadequate or Inferior Design	8
4.	Improper or Inferior Construction	8
5.	Hazards of the Elements	8
6.	Hazards of Operation	8
7.	Obsolescence of Live Load Capacity	20
8.	Obsolescence due to Lack of Need	8
		100%

In the case of the Delair Bridge, and when applied to most existing bridges, it can reasonably be stated that only factors 1, 2 and 6 are affected by the passage of time; and they are essentially proportional to expended service life. If then, only factors 1, 2, and 6 are found to cause depreciation and therefore to affect service life an equation for maximum possible life can be written:

$$\frac{0.20}{n} + \frac{0.20}{n} + 0 + 0 + 0 + \frac{0.08}{n} + 0 + 0 = \frac{1}{kn}$$

$$\frac{1}{2.08n} = \frac{1}{kn}$$

where kn equals the maximum possible service life.

Thus if the probable life new of a bridge substructure is 100 years, then the maximum possible life under this scenario is 208 years. If the probable life new of a bridge superstructure is 70 years, the maximum possible life under this scenario is 145.6 years.

After the passing of "m" years, we will have used m/kn of the maximum possible life and, re-evaluating formula (1), we now get:

$$\frac{1+m/kn}{n} = \frac{1}{e}$$ where "e" is the life expectancy beyond age "m",

or

$$e = \frac{kn^2}{kn + m}$$

However, as "m" reaches "kn", the value of "e" must be zero; therefore, the above expression must be corrected by adding a function of "m". The function of "m" required to satisfy this condition is m/2k and the formula becomes:

$$e = \frac{kn^2}{kn + m} - \frac{m}{2k}$$

It will be observed that, when "m" is zero, "e" equals "n"; and, when "m" is equal to "kn", "e" becomes zero. Also, repeating the definitions,

n = average life new assigned by I. C. C.
kn = maximum possible life
m = expended life or actual age
e = life expectancy beyond age "m"
n-e = equivalent years of expired service life at age "m"

For the superstructure of Bridge X, built in 1926

$n = 70$, $kn = 145.6$, $m = 66$ in 1992

$$e = \frac{145.6 \text{ x } 70}{145.6 \text{ x } 66} - \frac{66}{4.16}$$

$e = 48.2 - 15.9 = 32.3$ years

Thus the Delair Method would predict a total life of 98.3 years for a bridge supersructure already 66 years old.

3. Fatigue Service Life - The Grunsky Method, and to a lesser degree the Delair Method, are generalized formulations, non-specific to a particular bridge. They do not take into account, or only partially take into account, the physical condition, the circumstances, and the past history of a specific bridge. Fortunately, there is another tool now available, that of computing the remaining safe fatigue life of a structure and equating that life to the remaining service life. This newer tool is not merely a manipulation of mathematics, but rather a completely rational computation, founded in scientific research.

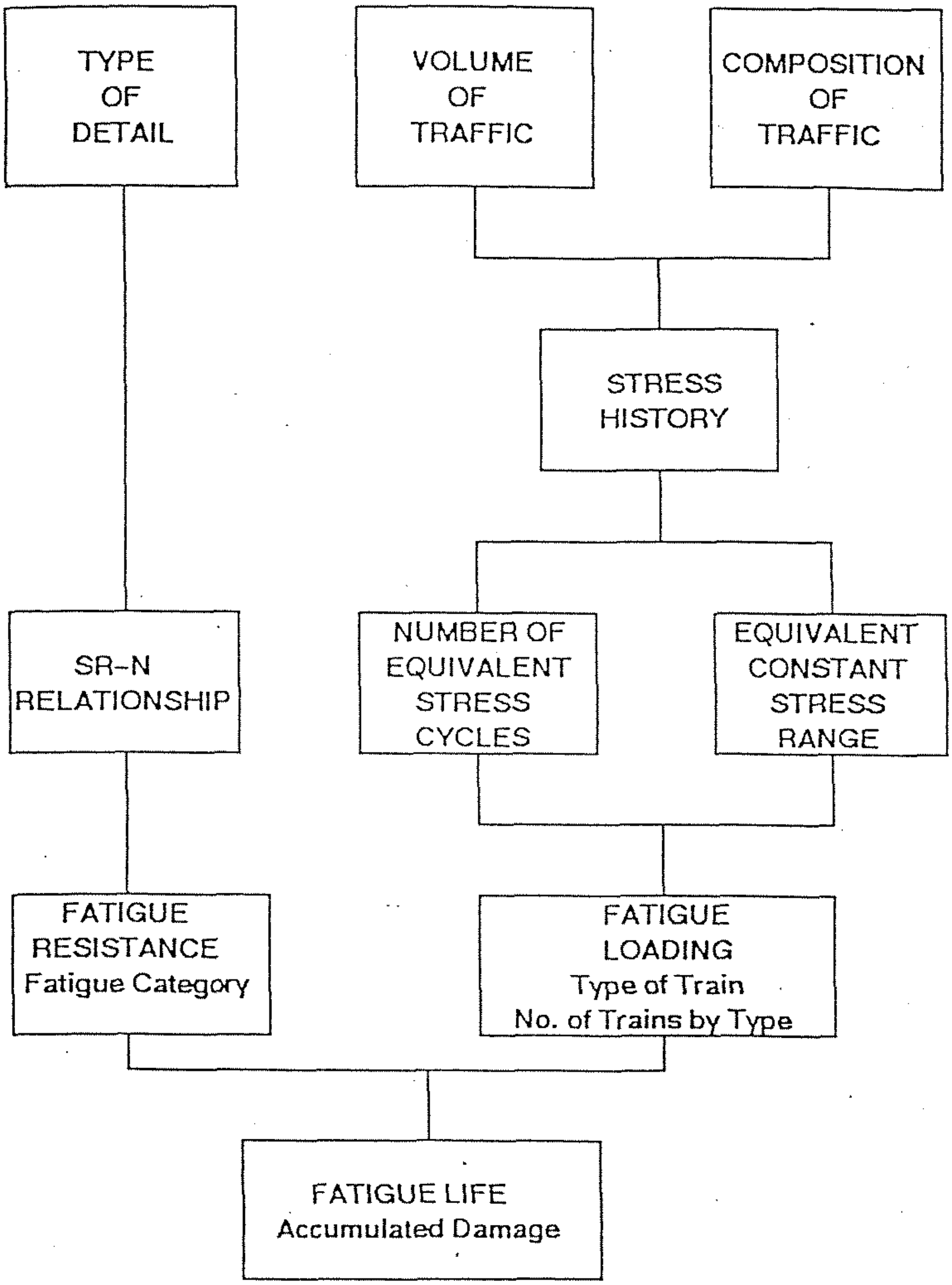
   Fatigue service life can be defined in terms of the number of cycles or the number of years until failure. When the fatigue resistance of a specimen is determined through testing, fatigue service life is defined as the number of repetitions of a given constant amplitude stress range before a crack develops. When referring to bridges, the term fatigue service life is usually related to a given number of years. In the case of existing bridges, fatigue service life includes the period of time from the beginning of service through the remaining life of the structure.

   The steps involved in determining the fatigue service life are as shown on the Flow Chart, in which the Fatigue Resistance of a detail is determined, expressed in terms of total number of cycles to first cracking, and then compared to the Fatigue Loading expressed in terms of number of stress range cycles applied per year, both in the past and in the future.

   The detail under investigation is evaluated and assigned an appropriate fatigue category. In order to assign a fatigue category to a given detail, the guidelines given in the A.R.E.A Specifications would be used for a railroad bridge. These guidelines are formulated for the design of new bridges and are on the conservative side. In some situations which are different from those covered by the Specifications, the evaluator would use his own judgement. This is particularly true when the field inspection shows severe corrosion or other defect which might lead to a lower than normal fatigue category.

   The Fatigue Resistance, in terms of number of cycles of a given stress range, is determined for each type of member on the bridge. This would include stringers, floorbeams, truss diagonals, truss verticals and truss chords.

   The Fatigue Loading would be determined by first collecting information on the composition and volume of traffic through the past life of the bridge and projecting the same or similar information into the future. Traffic composition is expressed in terms of typical trains, and traffic volume is expressed in terms of the number of trains by type. From this data, the stress history of the bridge members are developed, expressed in terms of number of cycles per year.



Flow Chart for Cumulative Damage Assessment Approach

The stress history depends on several factors, including the type of bridge, the type of member under evaluation, and the type and number of trains used throughout the life of the bridge. Adjustments for reducing the calculated stresses and the calculated impact factors to reflect actual conditions are included. Using the SR-N relationships, Miner's rule, the equivalent stress range concept, and a cycle counting method, the stress history is expressed in terms of equivalent constant stress ranges and numbers of equivalent stress cycles.

The remaining Fatigue Service Life is computed by determining how many of the allowable stress cycles are used to date and therefore how many remain for future use. The future allowable stress cycles are then compared to the predicted future loading cycles and the result expressed in terms of years.

As an example, for that same Bridge X used as an earlier example, the remaining minimum safe Fatigue Service Life, expressed in years from 1992, is computed as 33 years for the stringers of the approach spans. The minimum safe fatigue service life in the trusses is computed as 43 years in the approach trusses and 49 years in the swing span. In both trusses, the sub-hangers are the critical member. See Tables 1 and 2 for the complete tabulation of computed fatigue life remaining.

The results of any fatigue evaluation are strongly related to the assumptions made throughout the evaluation/computation process. Because of the conservative assumptions used, it is felt that the actual safe fatigue service life is undoubtedly somewhat greater than the values estimated here.

V. COMPARISON OF ANALYTICAL RESULTS

For each of the computation methods detailed above, an example has been given for a hypothetical Bridge X, built in 1926 and analyzed in 1992. The various service lives estimated by these methods for Bridge X are summarized below:

Superstructure	Grunsky Method	Delair Method	Fatigue Estimate
Approach Span Truss	27.3 yr.	32.3 yr.	43 yr.
Approach Span Floor System	27.3 yr.	32.3 yr.	45 yr.
Swing Span Truss	27.3 yr.	32.3 yr.	49 yr.
Swing Span Floor System	27.3 yr.	32.3 yr.	33 yr.

MEMBER	REMAINING FATIGUE SAFE LIFE (YEARS)		FAT CATGR	COMMENTS
	BASED ON PRESENT TRAFFIC	BASED ON 25% INCREASE IN PRESENT TRAFFIC		
BOTTOM CHORDS:				
L0-L2	900 +	866	D	
L2-L4	900 +	900 +	E	BASED ON STRESS RANGE @ EYEBAR HEAD
L4-L6	900 +	900 +	E	BASED ON STRESS RANGE @ EYEBAR HEAD
L6-L8	900 +	900 +	E	BASED ON STRESS RANGE @ EYEBAR HEAD
L8-L10	900 +	900 +	E	BASED ON STRESS RANGE @ EYEBAR HEAD
L10-L12	900 +	900 +	E	BASED ON STRESS RANGE @ EYEBAR HEAD
L12-L14	900 +	881	D	
DIAGONALS:				
U2-M3	900 +	868	D	
M3-L4	900 +	898	D	
U4-M5	587	470	D	
M5-L6	532	425	D	
U6-M7	286	229	D	
M7-L6	255	204	D	
M7-U8	315	252	D	
M7-L8	245	196	D	
L8-M9	357	286	D	
M9-U10	411	329	D	
L10-M11	900 +	780	D	
M11-U12	900 +	773	D	
VERTICALS:				
U2-L2	457	365	D	
U4-L4	900 +	900 +	D	
U6-L6	619	495	D	
U8-L8	638	510	D	
U10-L10	900 +	786	D	
U12-L12	745	596	D	
SUB HANGERS				
L1-M1	73	58	D	HIGHER ACT./ CALC. RATIOS FOR STRESS AND IMPACT
L3-M3,..	64	51	D	HIGHER ACT./ CALC. RATIOS FOR STRESS
L13-M13	53	43	D	HIGHER ACT./ CALC. RATIOS FOR STRESS AND IMPACT
STRINGERS:				
20'-6.5"	57	45	C	BASED ON STRESS RANGE @ RIVET HOLE LOCATION
15'-6.5"	80	64	C	BASED ON STRESS RANGE @ RIVET HOLE LOCATION
FLOORBEAMS:				
INTERIOR	149	119	C	
END	70	56	C	HIGHER ACT./ CALC. IMPACT RATIO @ END FLOORBEAMS
99 FT DECK GIRDER:	846	677	C	

TABLE 1 - REMAINING FATIGUE SAFE LIFE VALUES FOR 277'-7" TRUSS SPAN AND 99' DECK GIRDER SPAN

MEMBER	REMAINING FATIGUE SAFE LIFE (YEARS)		FAT CATGR	COMMENTS
	BASED ON PRESENT TRAFFIC	BASED ON 25% INCREASE IN PRESENT TRAFFIC		
BOTTOM CHORDS:				
L0-L2	304	256	D	
L2-L4	298	251	D	
L4-L6	73	62	D	
L6-L8	900 +	900 +	D	STAYS IN COMPRESSION
L8-L10	900 +	900 +	D	STAYS IN COMPRESSION
L10-L12	900 +	900 +	D	STAYS IN COMPRESSION
L12-L14	900 +	900 +	D	STAYS IN COMPRESSION
TOP CHORDS:				
U2-U4	151	130	D	
U4-U6	57	49	D	
U8-U10	153	135	D	
U10-U12	677	616	D	
U12-U14	900 +	900 +	D	
DIAGONALS:				
U2-M3	102	88	D	
M3-L4	106	92	D	
U4-M5	900 +	900 +	D	STAYS IN COMPRESSION
M7-L6	900 +	900 +	D	
M7-U8	900 +	900 +	D	
L8-M9	900 +	900 +	D	
M9-U10	900 +	900 +	D	
L10-M11	900 +	900 +	D	
M11-U12	900 +	900 +	D	
VERTICALS:				
U2-L2	458	366	D	
U4-L4	401	353	D	
U12-L12	483	387	D	
SUB HANGERS				
L1-M1	80	64	D	HIGHER ACT./CALC. RATIOS FOR STRESS AND IMPACT
L3-M3,..	73	58	D	HIGHER ACT./CALC. RATIOS FOR STRESS
L13-M13	61	49	D	HIGHER ACT./CALC. RATIOS FOR STRESS AND IMPACT
STRINGERS:				
19'-2"	41	33	C	BASED ON STRESS RANGE @ RIVET HOLE LOCATION
15'-6.5"	72	57	C	BASED ON STRESS RANGE @ RIVET HOLE LOCATION
FLOORBEAMS:				
INTERIOR	91	73	C	

TABLE 2 - REMAINING FATIGUE SAFE LIFE VALUES FOR 525' SWING SPAN

Bridge X, 66 years old in 1992 and in good condition, would be allowed only 4 more years of superstructure life by the COE and USCG 70-year guideline. By use of the Grunsky method, remaining superstructure service life would be estimated at 27 years and total life at 93 years. By use of the Delair method, a remaining superstructure service life of 32 years and total life of 98 years would be estimated. By use of the Fatigue Service Life analysis, a minimum remaining super-structure service life of 43 years and total life of 109 years is estimated for the bridge trusses. (and 33 years and 99 years for the Swing Span floor system)

It is believed that in drawing conclusions from these estimates, the ICC guidelines, as used by the USCG and COE in apportioning costs for replacement of existing bridges, should be judged clearly fallacious and in error, at least when applied to older bridges. It is felt that any of the three methods (Grunsky, Delair, Fatigue) give reasonable results but that the preponderance of weight should be given to the Fatigue Service Life method, since it is founded on a clear-cut scientific basis and since it takes into account the actual condition and details of the bridge, and the actual loading history of the structure.

VI. THE REAL WORLD

In an effort to determine the actual service life of movable bridges, a large sampling was made of actual movable bridges, most of which are still in service but some whose service lives have ended. Data was gathered from several sources but the primary source was the U.S. Coast Guard Publication CG 425-1 and CG 425-2, "Bridges Over Navigable Waters of the United States - Parts 1 and 2". This is essentially a listing of permit data for U.S. bridges, Part 1 covering the Atlantic Coast and Part 2 covering the Gulf Coast and Mississippi River System.

Data on a total of 847 movable bridges was extracted from the publications. Of these, 541 were highway bridges and 306 were railroad bridges. The data were classified by bridge type, (bascule, swing or vertical lift) and sorted into age groups by 10 year increments. The results of this sorting is shown for highway bridges on Figure 1 and for railroad bridges on Figure 2.

Note from Figure 1 that the preponderance of highway movable bridges in this sample are bascule bridges (250 out of 541) or swing bridges (227 out of 541), and that there are many bridges of both types older than the 50 year maximum life allowed by the COE/USCG guidelines. In fact, the sample included 232 (out of 541) bridges 60 years old or older, and the median highway movable bridge age was near 50 years.


Age of Existing Bridges
Highway
Number of Bridges
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Age (Years)
□ Bascule
+ Swing
◇ V. Lift

FIGURE 1

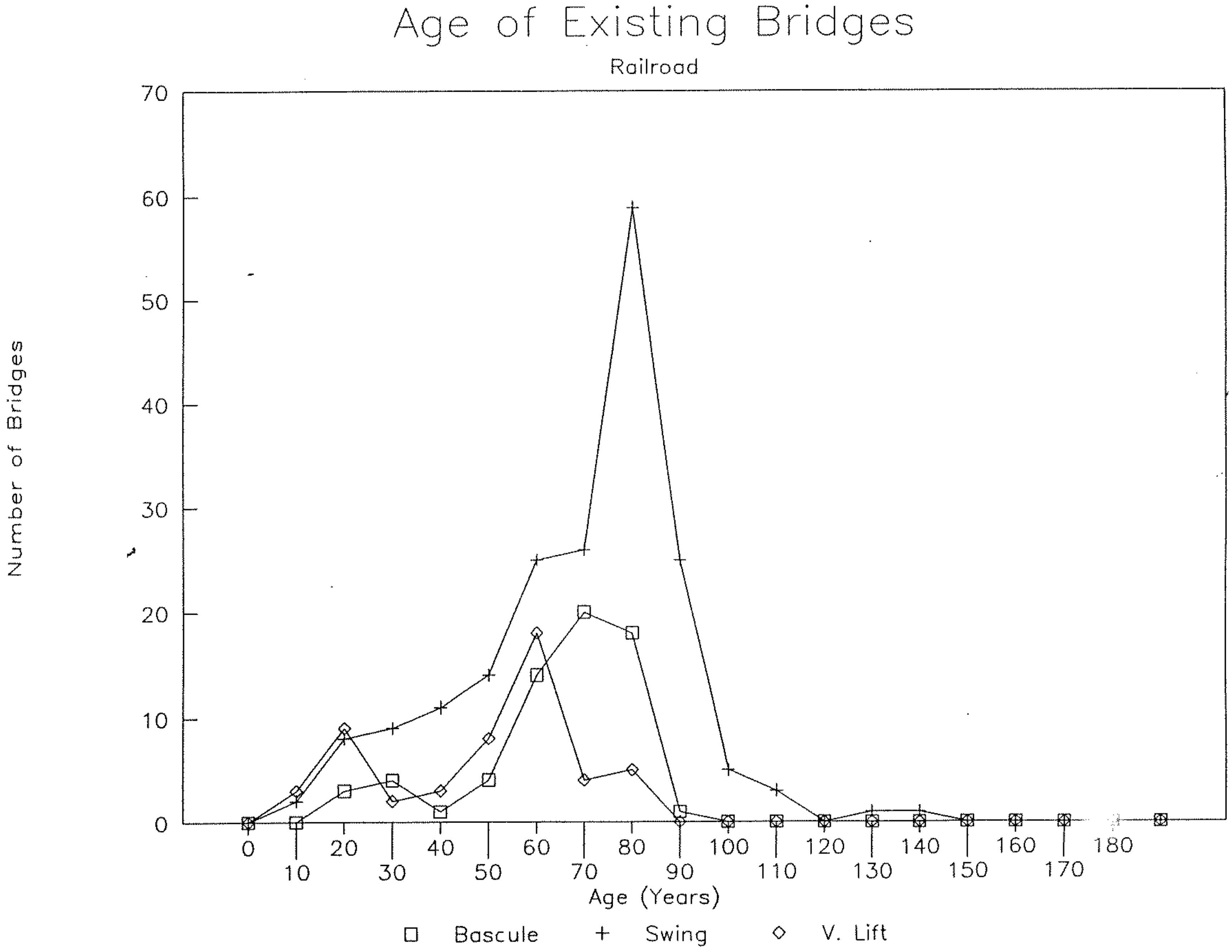

Age of Existing Bridges
Railroad
Number of Bridges
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Age (Years)
□ Bascule
+ Swing
◇ V. Lift

FIGURE 2

Likewise from Figure 2, it can be seen that the preponderance of railroad movable bridges are swing bridges (189 out of 306) and that there are many bridges older than the 70-year maximum life allowed by the COE/USCG guidelines. In fact, the sample included 118 (out of 306) bridges 80 years old or older, and the median railroad bridge age was near 70 years.

This sampling, flawed as it may be, supports the earlier conclusion that the COE/USCG figures for service life of movable bridges are to be viewed as average, not maximum figures.

The estimated remaining service life of a specific older bridge is, in our opinion, best determined by a Remaining Fatigue Life computation, supported and validated by a judicial application of the Grunsky and the Delair methods.