Bridge Management

Performance of Steel, Concrete, Prestressed Concrete, and Timber Bridges

Kim Stantill-McMcillan
Research General Engineer
USDA Forest Service
Forest Products Laboratory
Madison, Wisconsin
U.S.A.

Cherilyn A. Hatfield
Statistician
USDA Forest Service
Forest Products Laboratory
Madison, Wisconsin
U.SA.

Summary

The National Bridge Inventory (NBI) in the United States is a comprehensive document that maintains inventory records on all bridges 20 ft (>6 m) or greater in length. Although its records are primarily used by individual states and the Federal government for assessing bridge condition and assigning funding to future projects, the NBI has much useful data that can be used for other purposes, such as developing historical trends in bridge construction, adequacy, and longevity. Recently, the USDA Forest Service, Forest Products Laboratory (FPL), in cooperation with the USDA Forest Service Timber Bridge Informetion Resource Center, completed an analysis of the 1992 NBI to determine historical characteristics of concrete, steel, prestressed concrete, and timber bridges. Comparisons of bridge performance based on historical data were investigsted and are presented in is paper. Analysis on material usage, structural and functional adequacy, and longevity are included. The construction and performance trends revealed by the data will be useful to bridge designers and managers.

In: Developments in short and medium span bridge engineering '94: Proceedings of 4th International conference on short and medium span bridges; 1994 August 8-11; Halifax, Nova Scotia, Canada. Montreal, P.Q., Canada: The Canadian Society for Civil Engineering; 1994: 341-354.

INTRODUCTION

The United States has more than 3.9 million miles (6.3 million kilometers) of roadway (U.S. Department of Transportation, 1987) and mote than 575,000 bridges. In response to the December 1967 collapse of the Silver bridge over the Ohio River which claimed 46 lives, Congress mandated for the implementation of National bridge inspection standards. The individual bridge inspection records that are based on these standards constitute the National Bridge Inventory (NBI). The purpose of the NBI is to provide a uniform base of bridge information that can be used to identify those bridges that are most in need of repair and to serve as a basis for allocating Federal Highway Administration (FHWA) funding for bridge rehabilitation or replacement. The NBI is administered by the FHWA in Washington, DC, and data are updated continuously based on the latest bridge inspection; most inspections are completed on a 2-year cycle. The 1992 NBI contains inspection records for approximately 575,000 bridges 20 ft (6 m) or longer. Culverts that are 20 ft (6 m) or greater in span are included. The records include most, but not all, U.S. bridges. Excluded are. many bridges on Federal lands, including military installations.

The NBI contains a great deal of information that is potentially useful to bridge engineers. However, it is difficult for most engineers to access the NBI and display meaningful data in a useful format. To do this, the USDA Forest Service, Forest Products Laboratory (FPL), in cooperation with the USDA Forest Service Timber Bridge Information Resource Center, initiated a study to complete an analysis of the 1992 NBI. This analysis involved several hundred data sorts to obtain information related to bridge performance relative to such parameters as material type, roadway type, and bridge age. In addition to this general analysis, another analysis aimed specifically at timber bridges is currently in progress at FPL. Because they are of interest to many people, abbreviated results from the general analysis are presented in this paper. Results of the more specific analysis with an emphasis on timber bridge performance will be published at a later date.

BACKGROUND AND DEFINITIONS

The NBI was developed to provide a consolidated database of bridge, condition ratings. To accomplish this, bridges are rated by private individuals and government agencies, and the inspection data are coded into the NBI following a format outlined in the FHWA coding guide (U.S.Department of Transportation, 1988). Based on this inspection data, each bridge in the NBI is assessed a performance rating of structurally deficient, functionally obsolete, or satisfactory. Because the NBI analysis presented in this paper is directly linked to these performance ratings, a clear understanding of the definitions is necessary to understand the data analysis.

The definitions for structurally deficient (SD) and functionally obsolete (FO) used in this analysis follow the definitions used by the FHWA with one exception. The FHWA excludes bridges built or reconstructed within the last 10 years from being classified as SD or FO. In this analysis, the year limits were removed from the definitions in order to assess the rating adequacy of all bridges, including those built or reconstructed in the last 10 years. Definitions of the three performance ratings follow. For more specific definitions, refer to the FHWA coding guide.

Structurally Deficient

To be defined as SD, bridges must meet at least one of the following three criteria:

1. The condition of the deck, superstructure, or substructure is rated as poor (4) or worse. Condition ratings are assigned on a 10-point scale from failed (0) to excellent condition (9).

2. The structural evaluation, which accounts for the overall bridge condition, is rated 0 (closed), 1, or 2 on a scale of 0 to 9. The structural evaluation rating is based on the condition rating of the superstructure or substructure determined from criterion 1 and the overall load-capacity of the bridge.

3. The waterway adequacy, which is related to the frequency of flooding, is rated as not sufftcient. The acceptable frequency of bridge closure due to flooding is based on coding guide criteria depending on the importance of the roadway and the acceptable traffic delay. It is acceptable for a less important road to flood with greater frequency and to have longer traffic delays.

To a great extent, criteria for rating a bridge structurally deficient are associated with material performance of the superstructure, substructure, or deck. However, it must be recognized that a bridge may be rated SD based on criteria not related to material performance. For example, a bridge could be rated as SD even though the superstructure, substructure, and deck are in good condition because the load-carrying capacity does not meet agency standards or because. the waterway floods too frequently to be acceptable, usually because the bridge is situated too low.

Functionally Obsolete

After evaluating a bridge against the criteria for a SD rating, the nonstructurally deficient bridges are evaluated against criteria for a rating of functionally obsolete (FO). The criteria for a FO rating require that at least one of the following five conditions is met:

1. The deck geometry is too narrow for the volume and mix of daily traffic.

2. The vertical or horizontal underclearance is not adequate.

3. The approach roadway alignment requires a substantial reduction in vehicle operating speed. The magnitude of a substantial reduction in speed is a subjective assessment based on the inspector’s judgment.

4. The structural evaluation rating is 3. on a scale of 0 to 9. The rating is below that for a satisfactory bridge (4). but is higher than the rating for a bridge to he classified as SD. The structural evaluation rating indicates that the bridge requires corrective action.

5. The waterway adequacy is such that the frequency of flooding is less than that for SD

bridges, but still unacceptable. In addition, there are unacceptable delays caused by flooding of the bridge, but these delays are not frequent enough to classify the bridge as SD.

With the exception of the structural evaluation rating (item 4). FO ratings are based more on geometry and less on material performance.

Satisfactory

If a bridge is not defined as structurally deficient or functionally obsolete, it is rated satisfactory. A satisfactory rating indicates that the bridge meets agency standards for condition, load capacity, waterway adquacy, and geometry.

RESEARCH METHODS

The topics presented in this paper are performance of main span material, basis for classification of bridges as SD, roadway type on the bridge, deterioration rate by 5-year increment of year built, and age of the bridge. Within each of these areas, bridges were sorted according to the performance levels of structurally deficient, functionally obsolete, or satisfactory. To complete the general FPL analysis of the NBI, several hundred data sorts were performed.

The NBI data set was received directly from FHWA in May 1992, and the data analysis was completed on a *UNIX* workstation using SAS for data sorting. In order to make the large data set more manageable, it was modified at the FPL by deleting information including culvert records, nonvehicular bridges, and partial records of bridge inspections that were not related to the data analysis. Approximately 100,000 culvert records were deleted. Although the inventoty at FHWA is continually being updated, the data set was not updated once the analysis was started to maintain consistency in the results. Thus, natural disasters that significantly affected bridge conditions, such as the midwest flooding during the summer of 1993 or the Los Angeles earthquake in January 1994, are not reflected in the data.

Main Span Material

In order to determine the difference in bridge performance by material, the NBI data was first sorted into 10 categories for the main span material. Three of these categoties- (1) masonry, (2) aluminum, wrought iron, or cast iron, and (3) other-were deleted since they constitute less than 1 percent of the bridge materials. Bridges were sorted into the remaining seven categories: concrete, concrete continuous, steel, steel continuous, prestressed concrete, prestressed concrete continuous, and timber. A designation of continuous indicates that the bridge is continuous over more than one span, and therefore has less joints. These seven categories were further analyzed for performance differences according to roadway type, bridge age, and bridge length.

Although a bridge may be categorized in the NBI as steel, concrete, or timber, not all components are necessarily constructed of that material. For example, many steel bridges have timber decks, and some timber bridges have concrete decks. This is significant because a steel bridge may be rated deficient due to the condition of the concrete deck on the steel members. Unless the defects that cause a bridge to be deficient occur in the primary material, the deficiency is not correlated to the primary bridge material.

Basis for Classification of Bridges as SD

Bridges were classified as SD if they received a low rating in at least one of five categories: (1) deck, (2) superstructure (3) substructure, (4)-waterway capacity, or (5) load capacity. In order to determine if there was a relationship between the bridge material and these categories, bridges were sorted by material type and the categories. The data were organized to determine if the bridges had low ratings only in the deck, superstructure, or substructure: in a combination of any two of these components; or in all three components. Even if the deck, superstructure, and substructure were rated as not deficient, those bridges classified as SD reflect a deficient load or waterway capacity.

Roadway Type by Material

To determine the differences in bridge performance by material and roadway type, the seven bridge material categories were sorted according to three performance categories and six roadway types. The roadway types included interstate, U.S. numbered highway, State highway, county highway, and city street.

Deterioration Rates (Five-Year Increments)

To examine the effects of age on performance, bridges were sorted by 5-year age increments for each material. The sorts were divided into the number of bridges that were SD, FO, and satisfactory within each 5-year period. A complementary analysis was completed to determine the percentage of SD, FO, and satisfactory bridges normalized to 100 percent within each 5-year period.

Average Bridge Age

For each material, average bridge ages were calculated for the categories of SD, FO, and satisfactory. These data were based on the year the bridge was built, not the last year of reconstruction. The data were sorted in this manner since it is impossible to ascertain from the NBI the number of times a bridge has been rehabilitated between the date of original construction and the date of the last major rehabilitation. For example, if a bridge was originally built in 1910, rehabilitated in 1936, and rehabilitated again in 1965, the bridge would be listed under the year built (1910) and the last year of rehabilitation (1965). The data would show that 55 years elapsed before major rehabilitation, which would be inaccurate. However, in order for a bridge to retain the original date of construction, some portion of the original structure must remain. If the original structure is completely replaced, the dam of construction changes to the rehabilitation date.

RESULTS AND DISCUSSION

Results are presented for each data sort category. Within each category, results ate presented by bridge material and performance classification (SD, FO, and satisfactory).

Main Span Material

Performance of bridges by main span material is shown in Table 1. Prestressed concrete and prestressed concrete continuous demonstrated the highest percentage of satisfactory bridges (81 and 87 percent satisfactory, respectively). The lowest percentages of satisfactory bridges were for steel and timber (38 and 32 percent satisfactory, respectively). A higher percentage of continuous bridges were rated as satisfactory compared to bridges of similar material that are not continuous. The ratings for FO bridges were more uniform for different materials than were the SD ratings. The FO ratings for four materials (concrete, concrete continuous, steel, and steel continuous) were identical (21 percent). The percentages of FO bridges for prestressed concrete and timber were also identical (14 percent). These results are not unexpected, since the definitions for FO bridges are dependent more on geometry than material performance.

Basis for Classification of Bridges as SD

The basis for classification of a bridge as SD is presented in Table 2. Approximately half of the prestressed concrete continuous bridges were deficient as a result of the deck rating. Steel continuous bridges were also deficient primarily as a result of a low deck rating. Timber bridges had the lowest percentage of deficiency ratings for the deck and superstructure. Deficient substructure ratings were the primary reason for a SD rating on concrete and prestressed concrete bridges. For the entire U.S. bridge data set, inadequate load or waterway capacity was the primary reason for classification of SD.

Approximately 40 percent of timber bridges and 30 percent of steel bridges were determined to be SD, due to either inadequate load or waterway capacity. These bridges were not deficient as a result of material deterioration. These bridges were classified as SD possibly because the bridges were not designed for the state minimum load or because it was difficult for the inspector to accurately determine the load-carrying capacity of the bridge. Further analyses are underway to examine these reasons.

Roadway Type by Material

The performance rating of bridges by material and road type is shown in Fig. 1. Continuous and noncontinuous bridges of similar materials were not combined for this analysis, since it was obvious that these bridge data sets are not homogeneous. Continuous bridges, while not as numerous as noncontinuous bridges, are more equally divided between county, state U.S. numbered highways, and interstates. More than half (55 percent) of all U.S. bridges are located on county highways, and almost one-quarter (23 percent) are located on State highways. Thus, more than 75 percent of U.S. bridges are on State and county highways. Steel and timber bridges are predominate on county roads, and concrete bridges are more evenly divided between county and State highways.

Percentages of satisfactory bridges by material and road type are presented in Table 3, and are based upon the same data used for Fig. 1. Considering all U.S. bridges, the percentage of satisfactory bridges increased as the quality of the road increased. City streets had the worst ranking for every material. A higher percentage of interstate or U.S. numbered bridges were rated satisfactory compared to those on county or State highways, and bridges on State highways were better than those on county highways or city streets. Steel bridges had the best performance on the interstate system, and steel continuous and concrete had the best performance on both the interstate system and the State highways. Concrete continuous, prestressed concrete, and prestressed concrete continuous bridges had the best performance on county highways, and with the exception of city streets, the worst on the interstate. Timber performance was 70 percent better on U.S. numbered highways than on other road systems.

Deterioration Rates (Five-Year Increments)

Bridge performance by 5-year increment for each bridge material is shown in Fig. 2. With the exception of steel and timber bridges, the percentage of SD bridges increased in the latest 5-year increment for five bridge materials. For these materials, new bridges are being built with a higher SD rating than that in the previous 5-year increment from 1985 to 1989. Performance was compared to that in these years, since these are the newest bridges and should have the highest percentage of satisfactory ratings. Although the percentage increase is small, it represents hundreds of bridges nationwide, worth millions of dollars. As can be seen from Fig. 2, the percentage of satisfactory timber bridges has risen dramatically since the 1970s.

Average Bridge Age

For each material, average ages for the categories of SD, FO, and satisfactory bridges are shown in Table 4. Again, it should be noted that these data are based on the age of the bridge when originally built, and not the last year reconstructed. As can be seen from Fig. 2, the average age of satisfactory bridges was not dependent on material type. The average age of a satisfactory bridge for concrete, steel, and timber was 34, 35, and 35 years, respectively, indicating that the expected design life of a satisfactory bridge constructed of these materials is independent of material type. Certain bridge types such as steel continuous, concrete continuous, or prestressed concrete do not have enough service life to determine if the same relationship exists. However, other authors (Veshosky et al., 1993) have concluded that there are no statistically significant differences in the rates of deterioration of steel and prestressed concrete bridge superstructures.

OBSERVATIONS

The following observations are based on results of the FPL NBI analysis:

- Performance of continuous bridges is batter than that of noncontinuous bridges.
- The percentage of functionally obsolete (FO) bridges is similar for all bridges, regardless of material.
- The substructure is the most likely reason for concrete and prestressed concrete bridges to be rated as structurally deficient (SD).
- Decks are the most common reason why steel continuous and prestressed concrete continuous bridges are deficient. Timber bridges have the best deck and superstructure performance.
- Steel and timber bridges have the highest percentage of bridges classified as SD;

however, they also have the highest percentage of bridges classified as SD due to waterway or load capacity. Approximately 40 percent of timber bridges and 30 percent of steel bridges were determined to be SD as a result of either inadequate load or waterway capacity, not from material deterioration. However, an absolute conclusion cannot be reached without further investigation.

- Bridges on roads that are engineered to higher standards have a higher percentage of satisfactory bridges. Interstates have the highest percentage of satisfactory bridges, followed by U.S. numbered highways, State highways, county highways, and city streets.

- Steel and steel continuous bridges have the best performance on the interstate system, while concrete continuous, prestressed concrete, and prestressed concrete continuous bridges have better performance on county roads where less road salt may be used.

- Timber bridges have the best performance on U.S. numbered highways. These bridges may be designed for a higher load capacity and may also intersect less stream crossings, so a lower percentage of bridges may be classified as SD as a result of load or waterway capacity.

- The percentage of new SD bridges is increasing for all material types, with the exception of timber and steel bridges. Presumably, this increase is a result of greater demands placed on local budgets, leaving the States and counties to sometimes build new bridges that do not meet the State highway rating.

- The percentage of SD bridges varies for concrete steel and timber, but the average age of a satisfactory bridge is approximately 35 years for concrete, steel, and timber bridges. This information could have a significant impact on the material selection for bridges, as it suggests that the expected design life of a satisfactory bridge is independent of material selection. Thus, initial cost may be the most important factor in deciding between alternative structural designs. It also suggests that this is a reasonable design life to use for bridges.

- Timber bridges have had a better performance rate since the 1970s, when modular glulam timber bridges became more widely used.

ACKNOWLEDGMENTS

We are grateful to Michael Ritter, Research Engineer and Javier Font, General Engineer at the USDA Forest Service, Forest Products Laboratory in Madison, Wisconsin; Stephen Quintana, USDA Forest Service, Director at the Timber Bridge Information Resource Center in Morgantown, West Virginia; the Statistics Department at the Forest Products Laboratory; and Paul Linden of United States Department of Transportation in Washington, DC.

REFERENCES

1. U.S. Department of Transportation. 1987. Our Nation's highways: selected facts and figures. U.S. Department of Transportation, Federal Highway Administration, Office of Highway Information Management HPM-10/4-87 (35M)E.

2. U.S. Department of Transportation. 1988. Recording and coding guide for the structure inventory and appraisal of the Nation's bridges. U.S. Department of Transportation, Federal Highway Administration. Report No. FHWA-ED-89-044.

3. Veshosky, D., Beidleman, C.R., Buetow, G.W., and Demir, M. 1993. Comparative analysis of bridge deterioration rates. Report No. 93-05. ATLSS Engineering Research Center, Lehigh University, Bethlehem, PA.

Table 1—Performance of bridges by main span material

Material	Total bridges	Structurally deficient	Functionally obsolete	Satisfactory	SD (%)	FO (%)	Satisfactory (%)
Concrete	93,908	15,247	20,079	58,582	16	21	62
Concrete continuous	42,012	3,504	8,747	29,761	8	21	71
Steel	156,445	64,467	32,202	59,776	41	21	38
Steel continuous	42,986	5,709	9,211	28,066	13	21	65
PC	74,197	3,240	10,701	60,256	4	14	81
PC continuous	9,161	245	987	7,929	3	11	87
Timber	45,863	24,709	6,512	14,642	54	14	32
Total	464,572	117,121	88,439	259,012	25	19	56

[a]SD is structurally deficient; FO, functionally obsolete; PC, prestressed concrete.

Table 2—Basis for classification of bridges as structurally deficient by material

Material	Deck only	Super-structure only	Sub-structure only	Two of three locations[a]	All three locations[a]	Load or waterway capacity
Concrete	6	10	29	22	17	16
Concrete continuous	11	8	19	29	15	18
Steel	10	10	17	19	14	30
Steel continuous	31	10	20	16	7	16
PC	24	12	28	12	5	19
PC continuous	49	7	26	9	2	7
Timber	5	6	20	14	16	39
Total	10	9	20	18	14	29

[a]Deck, superstructure and substructure.

Table 3—Percentage of satisfactory bridges by material and road type

Material	City street	County highway	State highway	U.S. numbered highway	Interstate
Concrete	51	64	65	56	65
Concrete continuous	52	78	70	71	70
Steel	29	36	43	46	54
Steel continuous	46	65	68	67	68
PC	69	86	81	84	74
PC continuous	75	91	89	90	83
Timber	24	29	43	76	44
Total	47	51	62	64	67

Table 4—Average bridge age in years by material and performance level

	Age (years)			
Material	Total	SD	FO	Satisfactory
Concrete	40	54	47	34
Concrete continuous	32	51	37	28
Steel	46	56	45	35
Steel continuous	28	39	32	25
Prestressed concrete	20	30	24	19
prestressed concrete continuous	16	24	18	15
Timber	39	41	42	35
Total	36	51	40	29

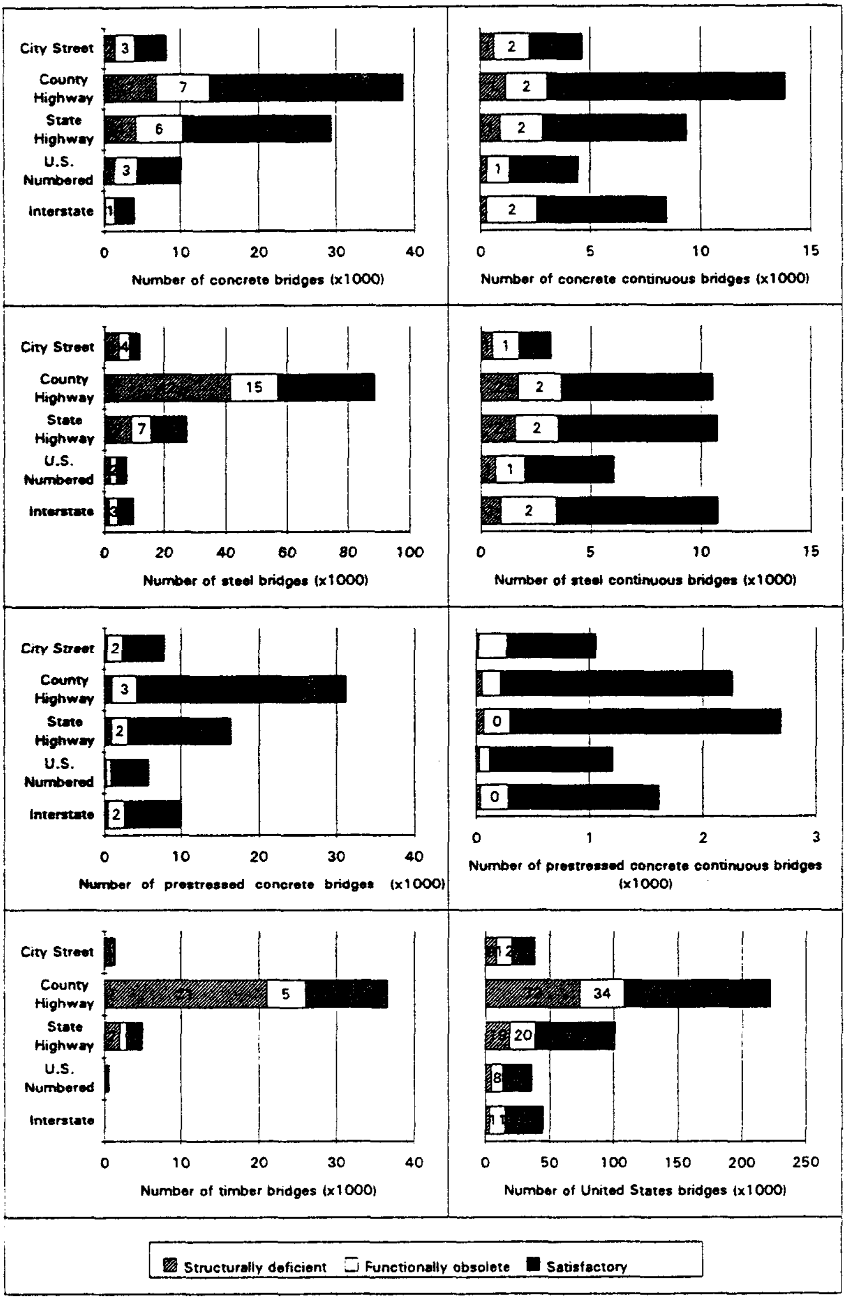

Figure 1: Bridges by material and road type.

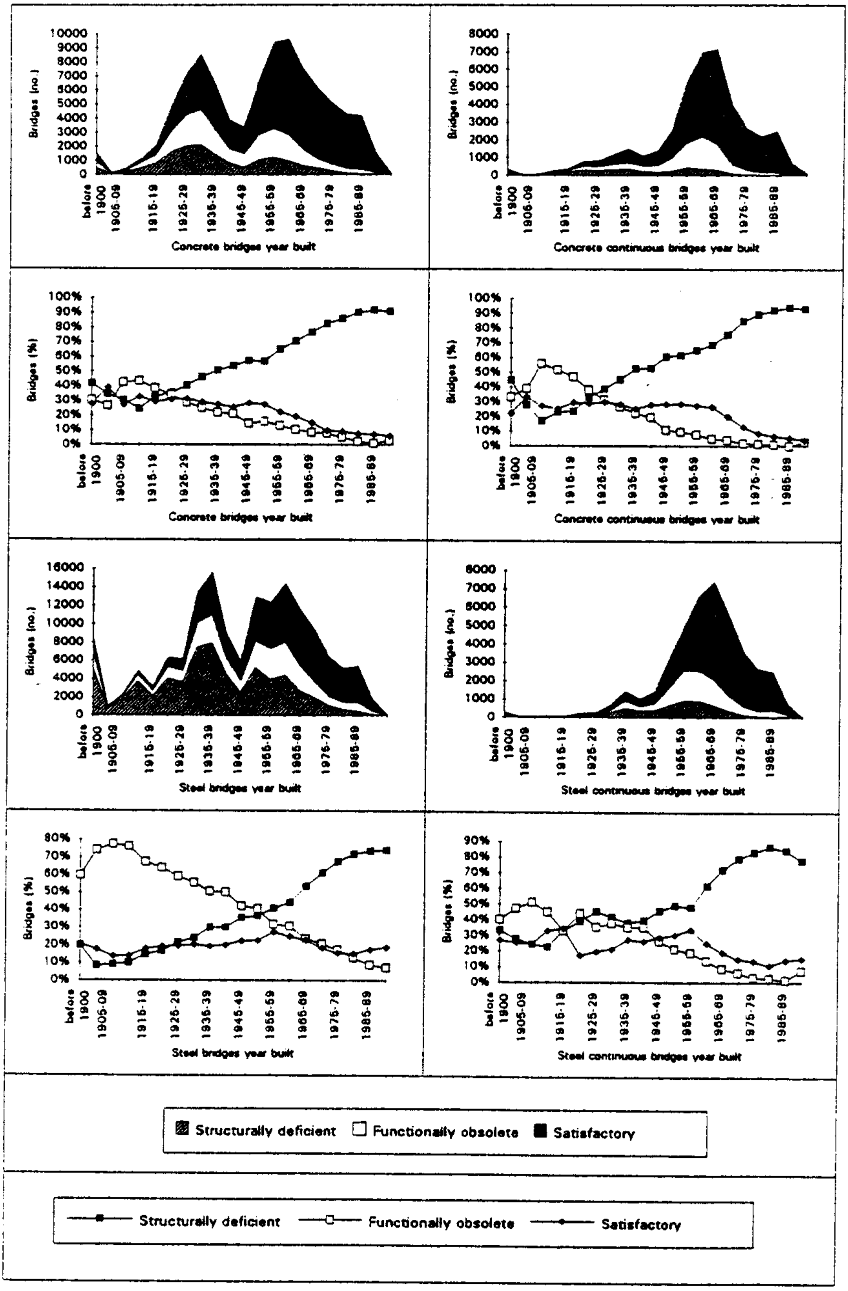

Figure 2: Deterioration rates in five-year increments by year built and material.

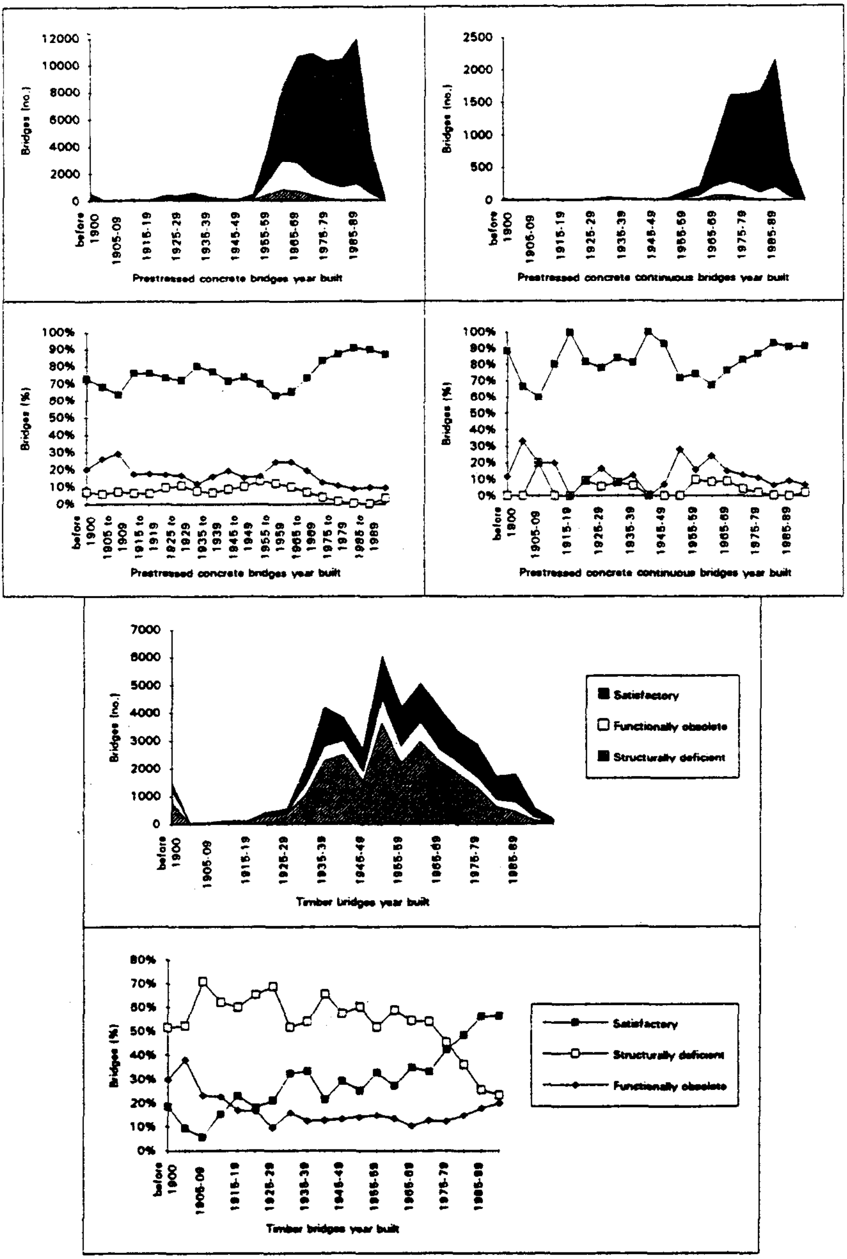

Figure 2 continued: Deterioration rates in five-year increments by year built and material.