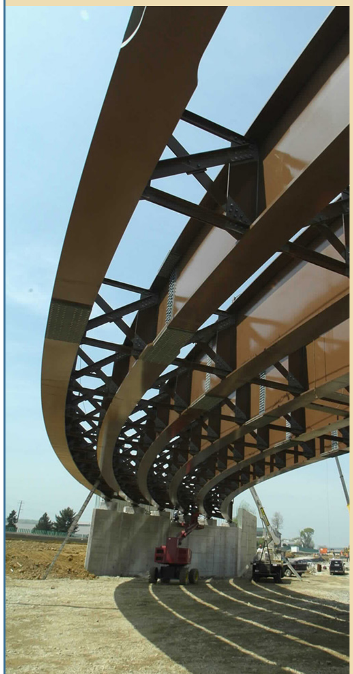

U.S. Department of Transportation
Federal Highway Administration

Steel Bridge Design Handbook

Redundancy

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Steel Bridge Design Handbook: Redundancy

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16. Abstract

In the context of steel bridge members, nonredundancy or fracture criticality relates to resistance of the entire bridge superstructure to brittle fracture. The question becomes, can a flaw or crack grow in an unstable manner as a brittle fracture resulting in the loss of the member and subsequently the loss of the superstructure? The issue of redundancy affects the design, fabrication and in-service inspection of steel bridge members when they are classified as fracture-critical members. Of all bridge construction materials, only steel bridge members are considered as candidates for the fracture-critical designation. This module provided engineers with the background concerning redundancy in steel girder bridges.

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Steel Bridge Design Handbook: Redundancy

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FOREWORD

It took an act of Congress to provide funding for the development of this comprehensive handbook in steel bridge design. This handbook covers a full range of topics and design examples to provide bridge engineers with the information needed to make knowledgeable decisions regarding the selection, design, fabrication, and construction of steel bridges. The handbook is based on the Fifth Edition, including the 2010 Interims, of the AASHTO LRFD Bridge Design Specifications. The hard work of the National Steel Bridge Alliance (NSBA) and prime consultant, HDR Engineering and their sub-consultants in producing this handbook is gratefully acknowledged. This is the culmination of seven years of effort beginning in 2005.

The new *Steel Bridge Design Handbook* is divided into several topics and design examples as follows:

- Bridge Steels and Their Properties
- Bridge Fabrication
- Steel Bridge Shop Drawings
- Structural Behavior
- Selecting the Right Bridge Type
- Stringer Bridges
- Loads and Combinations
- Structural Analysis
- Redundancy
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- Design Example: Three-span Continuous Straight Tub-Girder Bridge
- Design Example: Three-span Continuous Curved I-Girder Beam Bridge
- Design Example: Three-span Continuous Curved Tub-Girder Bridge

These topics and design examples are published separately for ease of use, and available for free download at the NSBA and FHWA websites: http://www.steelbridges.org, and http://www.fhwa.dot.gov/bridge, respectively.

The contributions and constructive review comments during the preparation of the handbook from many engineering processionals are very much appreciated. The readers are encouraged to submit ideas and suggestions for enhancements of future edition of the handbook to Myint Lwin at the following address: Federal Highway Administration, 1200 New Jersey Avenue, S.E., Washington, DC 20590.

Myint Lwin

M. Myint Lwin, Director
Office of Bridge Technology

1.0 DEFINING REDUNDANCY

1.1 General

The dictionary defines redundant as "exceeding what is necessary or normal," and provides "superfluous" as a synonym. Traditionally, bridge members have been classified as redundant or non-redundant by the designer by merely looking for alternative load paths. If you were to poll a group of bridge designers, most would consider four parallel members as redundant and two parallel members nonredundant. The redundancy of three parallel members is debatable. The question of the sufficiency of these alternative load paths to carry the additional load was not an issue.

A good, concise, universally accepted definition of redundancy does not currently exist in the bridge design or evaluation specifications.

1.2 Steel Bridges

The issue of redundancy affects the design, fabrication and in-service inspection of steel bridge members when they are classified as fracture-critical members. Of all bridge construction materials, only steel bridge members are considered as candidates for the fracture-critical designation.

In the context of steel bridge members, nonredundancy or fracture criticality relates to resistance of the entire bridge superstructure to brittle fracture. The question becomes, can a flaw or crack grow in an unstable manner as a brittle fracture resulting in the loss of the member and subsequently the loss of the superstructure?

The National Bridge Inspection Standards (NBIS) (1) define a fracture-critical member as "a steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse."

The AASHTO Manual for Bridge Evaluation (2), a recent combination of the AASHTO Manual for Condition Evaluation of Bridges (3) and the AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges (4), provides the following definition: "fracture critical members or member components are steel tension members or steel components of members whose failure would be expected to result in collapse of the bridge."

With multiple interpretations for "failure," "probably," "expected" and "collapse," just as for redundancy, a good, universally accepted definition does not exist for fracture-critical members or bridges.

1.3 Redundancy Classifications

Three classifications of redundancy can be defined as:

1. load-path,
2. structural, and
3. internal redundancy.

1.3.1 Load-Path Redundancy

A member is considered load-path redundant if an alternative and sufficient load path is determined to exist. Load-path redundancy is the type of redundancy that designers consider when they count parallel girders or load paths. However, merely determining that alternative load paths exist is not enough. The alternative load paths must have sufficient capacity to carry the load redistributed to them from an adjacent failed member. If the additional redistributed load fails the alternative load path, progressive failure occurs, and the members could, in fact, be fracture critical. In determining the sufficiency of alternative load paths, all elements present (primary and secondary members) should be considered.

1.3.2 Structural Redundancy

A member is considered structurally redundant if its boundary conditions or supports are such that failure of the member merely changes the boundary or support conditions but does not result in the collapse of the superstructure. Again, the member with modified support conditions must be sufficient to carry loads in its new configuration. For example, the failure of the negative-moment region of a two-span continuous girder is not critical to the survival of the superstructure if the positive-moment region is sufficient to carry the load as a simply-supported girder.

1.3.3 Internal Redundancy

A member is considered internally redundant if alternative and sufficient load paths exist within the member itself such as the multiple plies of a riveted steel member.

2.0 AASHTO FRACTURE CONTROL PLAN

2.1.1 A Fracture Control Plan for Steel Bridges

The genesis of the American Association of State Highway and Transportation Officials (AASHTO) fracture control plan can be traced to the collapse of the Point Pleasant Bridge over the Ohio River between Point Pleasant, West Virginia, and Kanauga, Ohio, in 1967. (The bridge was more commonly called the Silver Bridge for its bright coating of aluminum paint.) This eyebar-chain suspension bridge collapsed due to the brittle fracture of one of the nonredundant eyebars supporting the bridge's main span.

In 1974, after much debate and compromise, Charpy V-notch (CVN) toughness criteria were adopted to insure resistance to fracture. In addition, restrictions on acceptable detail types and welding practices were included. This set of provisions for material selection, design and fabrication of welded steel bridge members continues today as AASHTO's fracture control plan for non-fracture critical members. These provisions have resulted in an acceptably low observed probability of brittle fracture in bridges constructed in their accordance with the provisions.

2.1.2 A Fracture Control Plan for Nonredundant Steel Bridge Members

Based upon concerns of the Federal Highway Administration (FHWA) about the safety of nonredundant steel bridge members against brittle fracture, the American Iron and Steel Institute (AISI) sponsored research that resulted in the adoption of AASHTO's Guide Specification for Fracture Critical Non-Redundant Bridge Members in 1978. Here are the initial additional requirements for what are defined as fracture critical members setting them apart from other bridge members. The Guide Specifications primarily mandates more stringent CVN requirements, and fabrication and shop inspection practices. The Guide Specifications are no longer published by AASHTO as these provisions exist in other current AASHTO documents.

2.1.3 Increased In-service Inspections

The collapse of the Mianus River Bridge carrying Interstate 95 in Greenwich Connecticut in 1983 due to corrosion product accumulation behind hanger plates of a pin-and-hanger assembly brought additional requirements for fracture critical members. The National Bridge Inspection Standards (NBIS) (1) were revised in 1988 requiring biennial hands-on inspections of fracture critical members.

2.1.4 Additional Reading

National Cooperative Highway Research Program (NCHRP) Synthesis 354, Inspection and Management of Bridges with Fracture-Critical Details (5), provides detailed background on the AASHTO fracture control plan for nonredundant welded steel bridge members.

3.0 NONREDUNDANT MEMBERS

3.1 Definition

A good working definition of a nonredundant member is a member that when damaged or removed from the structural system fails to satisfy a certain level of load carrying capacity, although not necessarily the original design load carrying capacity. In other words, if the bridge with the damaged member cannot carry an acceptable amount of live load (to be defined) in addition to the present dead load, the damaged member is classified as nonredundant.

Further, this is a member that refined analysis (as discussed below) cannot remove from the classification.

3.2 Examples

The girders of a two-girder welded steel bridge with widely spaced crossframes, without a bottom lateral bracing system and with a normal cast-in-place reinforced concrete deck would be classified as nonredundant. A more robust deck, closely spaced crossframes or a significant bottom lateral bracing system could result in these girders being classified as quasi-redundant if refined analysis demonstrates that the remaining components have sufficient strength to withstand the loads.

4.0 QUASI-REDUNDANT MEMBERS BY ANALYSIS

4.1 Definition

A quasi-redundant member is a member that would traditionally be classified as nonredundant but through refined analysis has been shown to be redundant.

4.2 Examples

An example of a bridge with quasi-redundant members is the channel bridge developed by Jean Mueller International (JMI) and validated by Highway Innovative Technology Evaluation Center (HITEC) of the American Society of Civil Engineers (ASCE). While this bridge system is a segmental concrete bridge, it best illustrates the concept of a bridge consisting of quasi-redundant members. The channel bridge system is so named because the bridge cross section looks like a channel with its legs pointing upward. The "legs" are segmental concrete girders; the "web" is the deck connecting them transversely. JMI proved to the satisfaction of HITEC that the loss of one of the two girders (for obviously a reason other than brittle fracture, perhaps vehicular collision) would not result in the loss of the entire superstructure due to re-distribution of the loads from the failed girder through the deck into the adjacent girder.

A more recent and topical example is the Marquette Interchange in Wisconsin where HNTB proved that a two-box girder steel cross section (A cross section which represents a "gray area" in practice.) is redundant based upon the criteria established in NCHRP Report 406, Redundancy in Highway Bridge Superstructures (6), discussed below. The "gray area" results from the fact that the structure has four top flanges and webs, but only two bottom flanges. Redundancy of the bottom flange was proven by a combination of the ability of the non-fractured girder to resist torsional load combined with the continuity of the girders that provide partial redundancy of the fractured girder.

5.0 REDUNDANT MEMBERS

5.1 Definition

Reworking the above definition of a nonredundant member yields a working definition for a redundant member; i.e., a member that when damaged or removed from the structural system satisfies a certain level of load carrying capacity, although not necessarily the original design load-carrying capacity. In other words, if the bridge with the damaged member can carry an acceptable amount of live load (to be defined) in addition to the present dead load, the damaged member is classified as redundant.

5.2 Example

The girders of a bridge with multiple parallel girders (say, four or more) of girder spacing of about 12 feet are classified as redundant as tradition dictates. Currently, no analysis is required for this traditional definition of redundancy.

6.0 SYSTEM FACTORS

6.1 AASHTO LRFD Bridge Design Specifications, 5th Edition (7)

One of the stated objectives of the development of the *AASHTO LRFD Bridge Design Specifications, 5th Edition* (referred to herein as the LRFD Specifications) (7) was to enhance the redundancy and ductility of our nation's bridges. The consequences of redundancy are included in the basic LRFD equation of Article 1.3.2 of the LRFD Specifications.

$$\sum \eta_i \gamma_i Q_i \leq \phi R_n$$

where:

η_i = load modifier, and is the product of factors relating to ductility, η_D, redundancy, η_R, and operational importance, η_I,

γ_i = load factor,

Q_i = force effect,

ϕ = resistance factor, and

R_n = nominal resistance.

Quantitative factors relating to the redundancy of a structural systems were not available during the development of the first edition of the LRFD Specifications, so a "placeholder" was provided in the form of η_R. The specified values of η_R of Article 1.3.4 of the LRFD Specifications were subjectively chosen by the AASHTO Subcommittee on Bridges and Structures. For structural systems with conventional levels of redundancy, the factor is 1.0. For nonredundant systems, the factor is 1.05, thus increasing the force effect. Conversely, for systems with exceptional levels of redundancy, the factor is 0.95 resulting in slightly less force effect. The load modifiers relating to redundancy are summarized in Table 1 below.

Table 1 Load modifiers relating to redundancy

CLASSIFICATION	LOAD MODIFIER
redundant (as designed in accord with the LRFD Specifications)	1.0
nonredundant	1.05
exceptionally redundant	0.95

Redundancy is an attribute of the structural system and thus theoretically should be on the resistance side of the equation. In the LRFD Specifications, the factors appear on the load side of the LRFD equation for practical purposes. When maximum load factors are applied to the permanent loads the load modifier is applied as shown in equation 1.3.2.1-2 of the LRFD Specifications. When minimum load factors are chosen, the inverse of the load modifier is used as shown in equation 1.3.2.1-3 of the LRFD Specifications.

6.2 NCHRP Report 406

In support of the LRFD Specifications, the National Cooperative Highway Research Program (NCHRP) initiated NCHRP Project 12-36 which resulted in NCHRP Report 406, Redundancy in Highway Bridge Superstructures (6). This research developed system factors for girder bridges which reflect the redundancy of the structural system by assessing the safety and redundancy of the system. Tables of system factors are given for simple-span and continuous girder bridges with compact negative-moment sections (an uncommon practice), respectively. The system factors are given as a function of number of girders in the cross section and girder spacing. The values of system factors range from a low of 0.80 to a high of 1.20. As these system factors are to be applied to the resistance side of the LRFD equation, they represent the inverse of the load modifiers of the LRFD Specifications. A value greater than 1.0 rewards redundancy; a value less than 1.0 represents a penalty.

Table 2 and Table 3 below are adaptations of the tables in NCHRP Report 406 (6). With "a distributed set of diaphragms" throughout the span, the values of the tables may be increased by 0.10.

Table 2 System factors for simple-span I-girder bridges

GIRDER	NUMBER OF GIRDERS			
SPACING	4	6	8	10
4 feet	0.86	1.03	1.05	1.05
6 feet	0.97	1.01	1.01	1.01
8 feet	0.99	1.00	1.00	1.00
10 feet	0.98	0.99	0.99	-
12 feet	0.96	0.97	-	-

Table 3 System factors for continuous span I-girder bridges

GIRDER	NUMBER OF GIRDERS			
SPACING	4	6	8	10
4 feet	0.83	1.03	1.04	1.03
6 feet	1.03	1.07	1.06	1.06
8 feet	1.06	1.07	1.07	1.07
10 feet	1.06	1.07	1.07	-
12 feet	1.04	1.05	-	-

The effects of girder spacing evident in the tables may appear to be counter-intuitive, but the researchers offer an explanation. They suggest that system factors tend to increase as the girder spacing increases from 4 feet to 8 feet since in narrower bridges the girders tend to be more equally loaded with little reserve strength available. For girder spacings above 8 feet, loads are not so equally distributed among the girders, and as the more heavily loaded girders go into the inelastic range, the more lightly loaded girders can pick up the load which is shed.

Further, the effects of continuity also appear to be counter-intuitive for the narrowest bridges (in other words, for girder spacings of 4 feet). For girder spacings above 4 feet, the system factors for continuous steel bridges are greater than those for simple-spans indicating more redundancy, on average 7% greater. Such is not the case for the steel bridges with girder spacings equal to 4 feet. While the authors discuss at length their opinion that continuous I-girders with non-compact negative-moment regions are nonredundant (in other words, they recommend applying a system factor of 0.80), they do not speak to this apparent inconsistency for continuous steel bridges with compact negative-moment regions. Most likely, it is a similar narrow-bridge effect as discussed earlier.

The values in the tables are presented in a manner suggesting more precision than is warranted based upon the inherent assumptions, and the assumptions themselves have been subject to debate (such as the need for compact negative-moment sections to consider continuous bridges redundant). The practicing bridge community has yet to embrace the systems factors of NCHRP Report 406 (6), and they have not been adopted by AASHTO for use in the LRFD Specifications.

More importantly, the Report developed criteria for redundancy and redefines redundancy as a damaged structure's ability to continue to carry load, safely and serviceably.

6.3 The AASHTO Manual for Bridge Evaluation (2)

At their 2005 meeting, the AASHTO Subcommittee on Bridges and Structures (SCOBS) adopted the AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges (4) with revisions elevating allowable stress (ASR) and load factor rating (LFR) to equal status with LRFR, as the AASHTO Manual for Bridge Evaluation (2). The Guide Manual was originally developed by a team including one of the authors of NCHRP Report 406 (6) and as such includes some aspects of that report. System factors similar to those of the Report are included as an alternative to system factors derived from the load modifiers of the LRFD Specifications. For most bridges, these alternative system factors are specified as 1.0, but for bridges deemed less redundant in NCHRP Report 406 (6), for example, two-girder bridges, three- and four-girder bridges with narrow girder spacing and widely spaced floorbeams supporting non-continuous stringers, the system factors are reduced to as low as 0.85. See Table 4 below.

Table 4 System factors from the AASHTO Manual for Bridge Evaluation (2)

SUPERSTRUCTURE TYPE	SYSTEM FACTOR
welded members in two-girder/truss/arch	0.85
riveted members in two-girder/truss/arch	0.90
multiple eyebar members in truss bridge	0.90
three-girder bridges with girder spacing ≤ 6 feet	0.85
four-girder bridges with girder spacing ≤ 4 feet	0.95
all other girder bridges and slab bridges	1.00
floorbeams with spacing > 12 feet and non-continuous stringers	0.85
redundant stringer subsystems between floorbeams	1.00

Some states (for example, Florida) using LRFR for rating and seeing the value of the approach of NCHRP Report 406 (6) are developing system factors for their own application using engineering judgment and analogies.

7.0 PROVING REDUNDANCY

7.1 Application

7.1.1 Theory

In the event of a member's brittle fracture, the survival of the superstructure (and its classification as a redundant member) is contingent upon the system's ability to safely redistribute the existing applied and internal loads.

7.1.2 Applied Load

Based upon our working definition of redundancy, an acceptable level of load-carrying capacity for the damaged superstructure must be agreed upon. Currently, the design literature does not provide a definitive answer. The Commentary to the LRFD Specifications provides some insight. It suggests that a two-tub girder cross section could be deemed quasi-redundant by analysis if the superstructure with one fractured bottom flange can carry the factored live load in the lanes striped on the bridge, not the factored live load of all of the design lanes. This may still be overkill; the required load factors must also be re-visited for the reliability of the damaged bridge.

NCHRP Report 406 (6) suggests that the required load be unfactored and consist of dead load plus two HS-20 trucks side-by-side (the design truck of the LRFD Specifications). Using unfactored loads as suggested by the authors of NCHRP Report 406 (6) may be more reasonable.

7.1.3 Internal Loads

The release of energy during the fracture should be modeled to determine if the superstructure can survive the event. In the design literature, an analogy exists for cable-stayed bridges which must be able to tolerate the loss of a cable. The Post-Tensioning Institute (PTI) suggests that the "lost" cable be replaced with an opposite force equal to 200% of the lost-cable force. This represents a dynamic load allowance (IM of the LRFD Specifications) or impact of 100%. One hundred percent impact is the extreme value and appropriate for the undamped cable-stay. Such an extreme value is not appropriate for the brittle fracture of an element of a steel member where damping in more significant. Further research and the resultant guidance is required for steel members. Ongoing research at the University of Texas suggests that the gain in strength due to rapid loading may offset the increase in load due to impact. In the meantime, 100% impact could be used as a test realizing its extreme conservatism.

8.0 ENHANCING REDUNDANCY

8.1 Design of New Bridges

The concept of acceptable new bridge designs with varying levels of redundancy as championed by the LRFD Specifications has not found favor among practicing bridge engineers. Tradition has lead to designers thinking of a bridge as redundant or nonredundant without varying degrees.

As demonstrated (though obtusely) by NCHRP Report 406 (6), bridges traditionally deemed redundant, multi-girder bridges, can be demonstrated to exhibit varying quantifiable degrees of redundancy based upon the number of girders and their spacing. Yet, if designers think of nonredundancy versus redundancy analogously with black versus white, the concept of enhancing redundancy equates to turning nonredundant bridges into redundant ones.

The easiest and most effective manner to enhance the performance of nonredundant bridges is the selection of high-performance steels (in other words, ASTM A709 HPS50W, HPS70W or HPS100W) with their inherent enhanced fracture toughness. Nonredundant bridge members, those classified as such and those proven to be quasi-redundant by analysis should be fabricated from high-performance steel. Redundant members need not be fabricated from high-performance steel, unless warranted by unusually special conditions.

8.2 Rating and Retrofit of Existing Bridges

The application of the system factors suggested in the AASHTO Manual for Bridge Evaluation (2) (see Table 4) to the rating of existing bridges could lead to inadequate ratings for bridges with nonredundant members such as two-girder bridges. For example, a two-girder bridge designed without the application of system factors would be rated with a system factor of 0.85 reducing its resistance by 15%. If this bridge does not rate now, is it significant? The bridge has not changed, but our thoughts on reliability and safety have. Prior to posting or retrofitting, the bridge system (primary and secondary members including the deck and appurtenances) should be analyzed to determine if it can be classified as quasi-redundant.

Two-girder bridges (or arches or trusses) designed in accord with the LRFD Specifications will actually be more reliable or safer than those designed in accordance with the older AASHTO Standard Specifications for Highway Bridges (8). The calibration of the LRFD Specifications "set the bar" at the level of safety in multi-girder bridges where the increased load distribution of more refined lateral live-load distribution factors compensated for the increased live load of the HL-93 notional live-load model. Two-girder bridges do not enjoy the load distribution enhancement. This little-recognized fact should be factored into the considerations of rating a bridge with nonredundant members but designed to the LRFD Specifications.

9.0 THE FUTURE

Work is under way within the steel-bridge industry, AASHTO and the FHWA to better define redundancy and fracture-critical member requirements. This work includes the revisions to specifications for design, fabrication and in-service inspection of those members ultimately deemed to be fracture-critical. Also, research statements for potential, future NCHRP projects to define the required load and analysis procedures to classify quasi-redundant members are in process. In the meantime, engineering judgment must be used in an analysis to prove redundancy of a member traditionally deemed fracture-critical.

10.0 REFERENCES

1. *National Bridge Inspection Standards* (NBIS), Code of Federal Regulations, Title 23, Part 650, Subpart C, 2006.

2. AASHTO, (2008). *AASHTO Manual for Bridge Evaluation, First Edition*, AASHTO, Washington D.C.

3. AASHTO, (1994). *AASHTO Manual for Condition Evaluation of Bridges*, Second Edition, AASHTO, Washington D.C.

4. AASHTO, (2003). *AASHTO Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges*, First Edition, AASHTO, Washington D.C.

5. Connor, R.J., Dexter, R. and Mahmoud, H., *Inspection and Management of Bridges with Fracture-Critical Details*, NCHRP Synthesis 354, Transportation Research Board, Washington, DC, 2005.

6. Ghosn, M. and Moses, F., *Redundancy in Highway Bridge Superstructures*, NCHRP Report 406, Transportation Research Board, Washington, DC, 1998.

7. AASHTO, (2010). *AASHTO LRFD Bridge Design Specifications*; 5th Edition, AASHTO, Washington D.C.

8. AASHTO, (2002*). AASHTO Standard Specifications for Highway Bridges*, Seventeenth Edition, AASHTO, Washington D.C.