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SMART BRIDGE: A TOOL FOR ESTIMATING THE MILITARY LOAD CLASSIFICATION OF BRIDGES USING VARYING LEVELS OF INFORMATION

Decision and Information Sciences Division

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ACKNOWLEDGMENTS

This report documents SMART BRIDGE, a prototype automated tool developed by Argonne National Laboratory (ANL) to help military engineers and planners quickly and accurately determine the capacity, or military load classification, of bridges. The U.S. Army Military Traffic Management Command Transportation Engineering Agency sponsored this work, with technical guidance provided by Elpidio Manoso III of that agency.

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ABSTRACT

A major consideration in planning and executing military deployments is determining the routes available for moving troops and equipment. Part of this planning ensures that all of the bridges along the routes can support the specialized equipment needed. Because few trained and experienced bridge analysts are available, an automated tool is required to help military engineers and planners quickly and accurately determine the capacity, or the military load classification, of bridges. However, because detailed information about each bridge may not always be available, the tool also needs to include alternative methods for estimating bridge capacities. SMART BRIDGE, developed by Argonne National Laboratory, provides this capacity. The tool consists of a collection of modules that interact with each other to accommodate various bridge types, analytical techniques, and database functions.

1 INTRODUCTION

Whenever military forces deploy, a wide variety of personnel, equipment, and supplies must be moved, and many transportation modes are used, including air, sea, rail, highways, and, possibly, inland waterways and pipelines. Extensive planning and preparation are needed to select the best transportation modes (e.g., aircraft, ships, rail cars, and trucks) and transportation routes. A major need in planning the ground portion of a deployment is determining the highways and roads available for moving convoys of vehicles containing personnel, equipment, and supplies. In forward areas, in particular, equipment, such as tanks, armored personnel carriers, and artillery, can be transported under their own power as individual vehicles.

When determining which highways and roads are available for a deployment, a planner must ensure that all of the bridges along a route can support the specialized military vehicles being transported. The U.S. military has adopted a vehicle and bridge classification scheme to facilitate

comparing the load-carrying capacity of a bridge with the loading generated by convoys of military vehicles. Military load classification (MLC) values are assigned to both vehicles and bridges. As long as the MLC of the largest vehicle in a convoy does not exceed the MLC of the bridge, the bridge can safely withstand occasional use by the convoy.

An accurate evaluation of the MLC of a bridge requires extensive measurements and knowledge of the components of the bridge and fairly sophisticated engineering calculations. The U.S. Department of the Army (U.S. Army) is the primary user of ground transportation in forward areas, and it has established a set of analytical classification methods for use by Army combat engineers. These methods, simplified as much as possible but remaining consistent with good engineering practices, are described in detail in the Army field manual FM 5-446, *Military Nonstandard Fixed Bridging* (U.S. Army 1991). Even though somewhat simplified, these methods still require gathering vast amounts of information about the bridge, carrying out some time-consuming computations, and looking up parameter values in standard tables.

Under the direction and sponsorship of the U.S. Army Military Traffic Management Command Transportation Engineering Agency (MTMCTEA), Argonne National Laboratory (ANL) developed an automated tool to guide the combat engineer through the process of gathering the information required to classify a bridge and to complete the analytical classification process. The automated tool, referred to as SMART BRIDGE, also includes a database management capability for storing and retrieving bridge information. In addition, because all the measurements and other attributes of a bridge needed for analytical classification are often unavailable, SMART BRIDGE includes less precise methods for classifying bridges, creating a single system that captures and automates a range of bridge-related support for ground transportation planning.

SMART BRIDGE is designed for a variety of uses within the military. First, engineers and reconnaissance personnel in the field can accurately analyze bridges. Using SMART BRIDGE installed on a laptop computer allows engineers and reconnaissance personnel to enter and record information about the bridge at the bridge, as the components of the bridge are measured. Once they have entered the required attributes, the MLC of the bridge can be estimated immediately by automatically performing standard bridge analysis computations established by the U.S. Army.

Second, SMART BRIDGE captures all of the bridge's characteristics and analysis results in a database that planners can use for evaluating alternative deployment routes. Import and export routines incorporated in SMART BRIDGE allow each engineer or reconnaissance unit to exchange its records with units that have successively larger areas of responsibility until eventually all records are included in a central worldwide database of bridges.

Third, military planners can use SMART BRIDGE to estimate the MLC of bridges when detailed, hands-on measurements of the bridges are not available, such as for routes behind enemy lines. The system estimates, with a lower level of confidence, the MLC of a bridge on the basis of

a few characteristics that might be available from other sources, such as remote imagery and general knowledge of the region in which the bridge is located.

Finally, SMART BRIDGE is an ideal training tool for assisting new Army combat engineers in learning and applying classification techniques and expertise.

The remainder of this report is organized into several sections. Section 2 provides a brief overview of the bridge and vehicle classification system used by the military. The programming languages, computer platforms, and database management systems (DBMSs) used by SMART BRIDGE are discussed in Section 3. Section 4 describes how bridge records are created in the SMART BRIDGE database and how bridge and span information is entered. Section 5 summarizes the general approach used in the analytical classification procedures extracted from FM 5-446. Section 6 discusses the approximate classification of bridges by using limited bridge information correlated to civilian design and rating standards. The output from SMART BRIDGE is described in Section 7, along with methods for assigning confidence levels to the classification results. Finally, Section 8 summarizes SMART BRIDGE efforts and possible future work.

2 BRIDGE AND VEHICLE CLASSIFICATION

The U.S. military uses the vehicle and bridge classification system established by the nations of the North Atlantic Treaty Organization (NATO) through international agreement. Within this system, vehicles are assigned MLC numbers that represent the size of the vehicle and the loading effects that it has on a bridge. The MLC of a vehicle depends on a combination of factors, including gross weight, number of axles, axle spacing, axle width, and weight distribution to the axles. Similarly, bridges are assigned MLC numbers that represent the largest vehicle classification that the bridge can safely support as part of an occasional convoy with the vehicles spaced 100 ft apart and traveling at a maximum speed of 25 miles per hour. The MLC of a bridge is the MLC of its weakest span and depends on such factors as the length of the span, the type of construction, the quantity and size of the structural members, the strength of the materials used, and the width of the roadway. In preparing for ground movements of personnel, equipment, and supplies, military planners must compare the MLCs of vehicles to be moved with the MLCs of bridges along *potential* transportation routes.

The MLC scale is defined in terms of a set of 16 hypothetical standard wheeled vehicles and a set of 16 hypothetical tracked vehicles. Originally, these hypothetical vehicles were typical of actual military vehicles used in NATO countries. Standard tracked vehicles are designated by MLC numbers ranging from 4 to 150, which correspond to the gross vehicle weight in short tons. In addition to gross weight, each standard tracked vehicle is defined in terms of track width, length, and spacing. Standard wheeled vehicles are designated by the same MLC numbers (4 through 150), which correspond to about 85% of the gross weight in short tons. Each standard wheeled vehicle is defined in terms of gross weight, number of axles, axle spacing, and axle load. In addition to the standard hypothetical wheeled vehicles, a maximum single-axle load is specified for each MLC (used to represent the loading on very short spans when only one axle is on the span at a time). The details of these hypothetical standard vehicles are described in Table C-1 of Appendix C of FM 5-446.

The U.S. Army has developed a set of analytical procedures to assign MLC values to existing bridges. These procedures are described in Chapter 3 of FM 5-446. The MLC values differ for wheeled and tracked vehicles and for one- and two-lane operation. Up to four MLC values can be assigned to a single bridge. These procedures assume that the bridge superstructure is the controlling or limiting feature in bridge classification. The substructure, which includes footings, abutments, piers, piles, posts, and other supports, is usually overdesigned to compensate for uncertainties in the underlying soil properties. The details for the analytical procedures depend on the type of construction used for the bridge (e.g., timber, steel, reinforced-concrete, or prestressed-concrete stringers; steel girders or trusses; steel, concrete, or masonry arches; or suspension).

However, generally one or more of the following seven factors are examined, and the most restrictive factor limits the MLC values assigned to the bridge:

- Bending moments that induce bending stresses in structural elements that exceed the allowable limits of the construction material,
- Bending moments that cause vertical deflections of structural elements that can disrupt the bridge,
- Bending moments that create a potential for the lateral buckling of structural elements,
- Shear forces that induce shear stresses in structural elements that exceed the allowable limits of the construction material,
- Bearing forces that induce bearing stresses in structural elements or supporting members that exceed the allowable limits of either construction material,
- Individual tire loads that exceed the strength of the bridge deck, and
- Required lane widths that exceed the roadway width over the bridge.

The bending moments and the shear and bearing forces induced in the structural elements of a bridge span arise primarily from three sources: the dead load of the span superstructure, the live load of the vehicles on the span, and the impact load of the vehicles moving onto or off of the span. These general relationships can be expressed as follows:

$$m = m_{DL} + m_{LL} + m_{IL} \quad , \tag{1}$$

and

$$v = v_{DL} + v_{LL} + v_{IL} \quad , \tag{2}$$

where:

m = total induced bending moment per structural element;

m_{DL} = contribution to the bending moment due to the dead load;

m_{LL} = contribution to the bending moment due to the live load;

m_{IL} = contribution to the bending moment due to the impact load;

v = total induced shear force per structural element;

v_{DL} = contribution to the shear force due to the dead load;

v_{LL} = contribution to the shear force due to the live load; and

v_{IL} = contribution to the shear force due to the impact load.

The dead-load bending moment and shear force per structural element depend on the weight of the materials that make up the superstructure, the number of structural elements, and the length of the span. The live-load bending moment and shear force per structural element depend on the particular vehicles on the span, their spacing, and their speed. The live-load moment and shear force per structural element also depend on the length of the span and the effective number of structural elements per lane of traffic. That is, the effect of the live load is distributed by the deck to several structural members. The impact load is usually approximated as being proportional to the live load. Therefore, the bending moment and shear force due to the impact load can be expressed as:

$$m_{IL} = I\, m_{LL} \quad , \tag{3}$$

and

$$v_{IL} = I\, v_{LL} \quad , \tag{4}$$

where I is an empirical impact factor.

Substituting Equations 3 and 4 in Equations 1 and 2 yields:

$$m = m_{DL} + (1 + I)\, m_{LL} \quad , \tag{5}$$

and

$$v = v_{DL} + (1 + I)\, v_{LL} \quad . \tag{6}$$

For concrete spans, the analytical procedures developed by the Army include safety factors that effectively increase the estimated dead- and live-load bending moments. Equation 5 can be rewritten to include safety factors:

$$m = (1 + f_{DL})\, m_{DL} + (1 + I)\, (1 + f_{LL})\, m_{LL} \quad , \tag{7}$$

where:

f_{DL} = dead-load safety factor, and

f_{LL} = live-load safety factor.

Equations 7 and 6 can be solved for the live-load moment and shear:

$$m_{LL} = [m - (1 + f_{DL})\, m_{DL}]/[(1 + f_{LL})(1 + I)] \quad , \tag{8}$$

and

$$v_{LL} = (v - v_{DL})/(1 + I) \quad . \tag{9}$$

The analytical procedures in FM 5-446 use values of zero for both the dead- and live-load safety factors for timber and steel spans; for concrete spans, they use values of 0.4 and 0.7 for dead- and live-load safety factors, respectively. The value of the impact factor is zero for timber spans and 0.15 for steel and concrete spans.

If m and v are interpreted as the maximum allowable total bending moment and shear force that an individual structural element can sustain, Equations 8 and 9 can be used to calculate the maximum allowable bending moment and shear force that a structural element can support due to the live or vehicle load. The maximum allowable total bending moment and shear force depend on the cross-sectional properties of the structural element and the maximum allowable stress to which the construction materials can be exposed. The cross-sectional properties include the dimensions of the structural element and, for a concrete element, the location and quantity of the reinforcing or prestressed steel. The maximum allowable stress is usually assumed to be some fraction of the strength of the material. For steel spans, the analytical procedures in FM 5-446 suggest 0.8 and 0.49 times the yield strength of the steel for the maximum allowable bending stress and shear stress, respectively. The maximum allowable stresses for timber spans depend on the type of timber used. For reinforced-concrete spans, the maximum allowable bending stress is estimated as 0.9 times the yield stress of the reinforcing steel. For prestressed-concrete spans, the maximum allowable bending stress is estimated as 0.9 times either the allowable stress in the prestressed steel or the 28-day strength of the concrete, depending on which is the most limiting. Limits due to shear forces are not considered in the analyses of concrete spans.

Once the maximum allowable live-load bending moment and shear force per structural element (m_{LL} and v_{LL}) have been calculated, the maximum allowable live-load bending moment and shear force per lane of traffic for one- and two-lane operation (M_{LL1}, M_{LL2}, V_{LL1}, and V_{LL2}) are estimated. These estimates are made by multiplying the bending moment per structural element by empirical estimates of the effective number of structural elements per lane of traffic for one- and

two-lane operation (N_1 and N_2) and by multiplying the shear force per structural element by other empirical estimates of the effective number of elements per lane (N_1' and N_2'):

$$M_{LL1} = N_1 \, m_{LL} \quad , \tag{10}$$

$$M_{LL2} = N_2 \, m_{LL} \quad , \tag{11}$$

$$V_{LL1} = N_1' \, v_{LL} \quad , \tag{12}$$

and

$$V_{LL2} = N_2' \, v_{LL} \quad . \tag{13}$$

In general, the effective number of structural elements per lane of traffic depends on many factors. These factors include the type, number, and spacing of the structural elements; the type of deck supported by the structural elements; the width of the roadway relative to the length of the span; the number of lanes of traffic; and whether bending moments or shear forces are being assessed.

Finally, limiting MLC values based on bending moments and shear forces can be assigned to the span by comparing the maximum allowable live-load bending moments and sheer forces (calculated by means of Equations 10–13) with the maximum live-load bending moments and sheer forces induced by convoys of the 16 standard wheeled vehicles and the 16 standard tracked vehicles. The NATO countries have calculated and agreed upon these maximum induced bending moments and shear forces. Tables and plots of the calculational results are available in several U.S. Army publications, such as Appendix C of FM 5-446.

3 SYSTEM DESIGN

SMART BRIDGE was implemented by using the Application Interface Engine (AIE), a software tool created at ANL to facilitate development of applications that use graphical display and database access. The AIE is described in Fuja and Widing (1992). By using the AIE, the components of an application can easily be isolated for portability and maintainability. In addition, the same source code can be compiled for use on either UNIX or personal computer (PC)-based systems.

SMART BRIDGE consists of a series of modules that perform various functions, such as gathering information from the user, performing the calculations associated with a particular analysis method, generating printed reports, and interfacing with a database system. Information is entered (and the system controlled) through a graphical user interface that consists of a series of windows. Although slightly different in appearance, the same windows are used in both the UNIX and PC implementations of the system, and the same calculations are performed. To help the user gather and enter the required information about a specific bridge, SMART BRIDGE windows include Help buttons for quick access to material that describes each window and each data entry item in the window. Both textual and graphical materials are provided, including labeled diagrams of typical bridge structures and annotated photographs of actual bridges. The general approach to data entry is discussed in Section 4.

In contrast, the database management function differs in the two implementations. The UNIX implementation is intended for use in an office environment on a SUN platform. It uses the ORACLE™ relational DBMS, designed to handle very large databases, and requires a substantial computing platform. The PC implementation is intended for use in the field on a laptop computer to collect bridge information and perform rapid analyses. It uses CodeBase™ to create and manipulate FoxPro™ formatted database files and is intended to handle information about only several hundred bridges at a time. The actual data contents maintained in both systems are the same. In addition to textual and numerical information about bridges, both databases provide for links to files that contain digitized photographs or sketches of the bridges.

4 DATA ENTRY AND STORAGE

To classify bridges accurately, military engineers must know what bridge attributes are important; how the attributes relate and interact with each other; how to measure or otherwise determine these attributes; how to calculate dead loads, bending moments, and shear stresses; and how to assign MLC values on the basis of the calculations. SMART BRIDGE captures much of this expertise in a series of attribute input screens, automated attribute links, on-line help documents and diagrams, database tables, computational routines, and report generation facilities.

A bridge consists of one or more spans. The spans that make up a bridge are either of the same type or a variety of types of construction. Detailed information about each individual span is needed to assign MLC values to the span; general information about the bridge as a whole is needed for transportation planning. The detailed information needed depends on the type of construction and includes the number and dimensions of the structural components, the strengths of the materials, and the weights of the components. The general information needed includes the location and name of the bridge, the highway or road carried by the bridge, the condition and nature of the approaches to the bridge, the feature crossed by the bridge, and the availability of nearby bypass routes. A series of screens guides the user through the data input process. Once collected, all information about a particular bridge and its spans is stored as a record in a database.

4.1 CREATING A BRIDGE RECORD

When a user wants to add a new record to the database, SMART BRIDGE displays a Create Bridge Window (Figure 1). The user then enters basic information about the new bridge and its spans. The first three data fields (Bridge ID, Creator, and Country Code) form a unique key for identifying and linking the components of the record in the database. The country in which the bridge is located must correspond to an entry from an established list of 406 countries, states, seas, and other areas published as a Federal Information Processing Standard by the National Institute of Standards and Technology of the U.S. Department of Commerce. The Country can either be selected from a table, entered as a standard two-character code, or entered as a name. The Creator is the name or designation of the organization or individual responsible for the bridge record. The Bridge ID is a unique identifier for the bridge in the specified Country under the responsibility of the specified Creator.

At this point, the user enters basic information about each span. This information includes the span length, the span construction type, and the boundary condition with the next adjoining span, if one exists. By convention, the spans of a bridge are numbered in sequence starting with the westernmost span. If the bridge is essentially oriented in a north-south direction, numbering starts

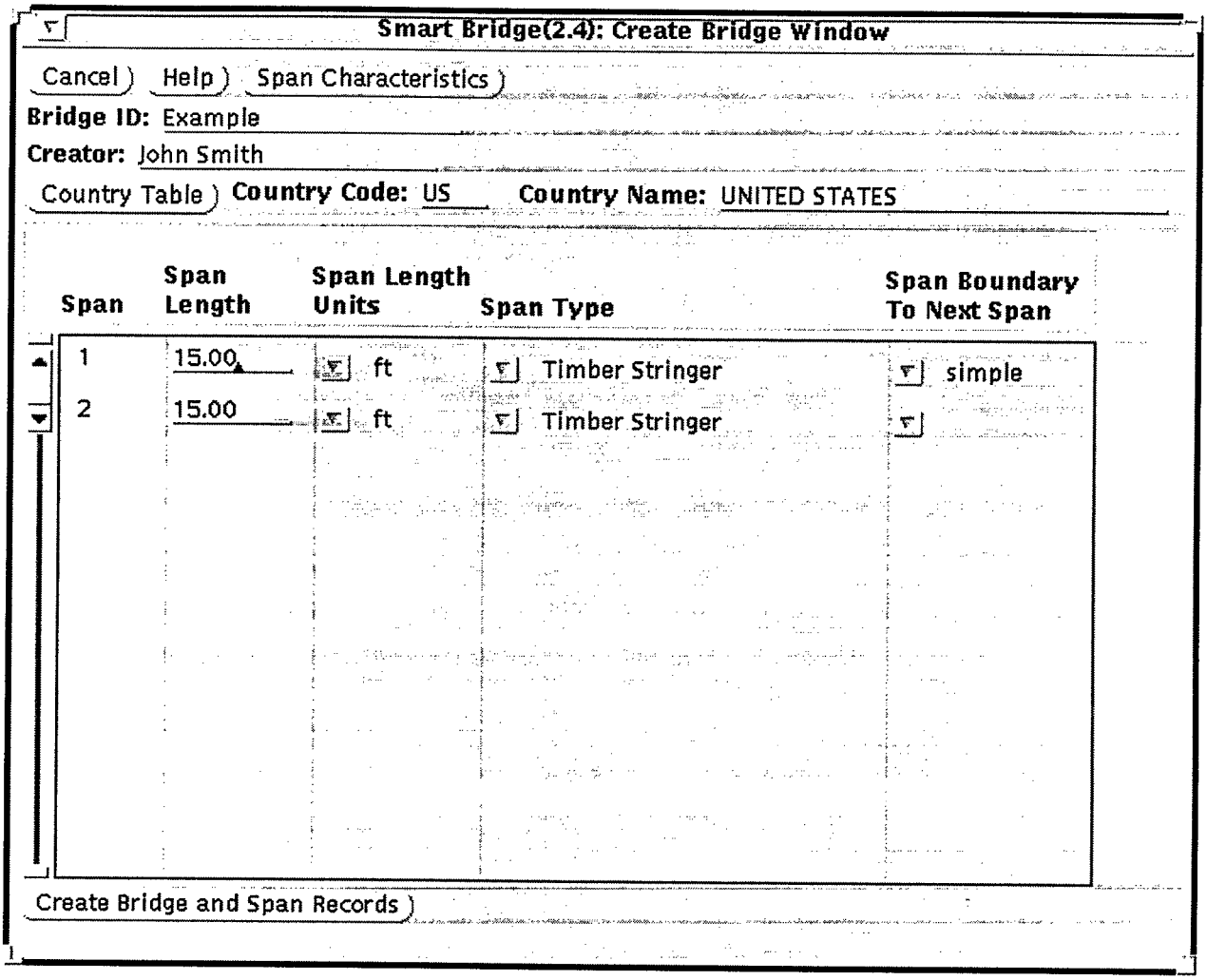

FIGURE 1 Create Bridge Window

with the northernmost span. The user selects the measurement units to be used in specifying the span length from an established list.

The user also selects the span construction type from a list based on the span types described in FM 5-446. This list will eventually include about 16 construction types that fall into two general categories. The first category includes stringerlike spans in which several structural members made of timber, steel, or concrete extend across the span and directly support a deck of timber, concrete, or steel grating. The structural members are often referred to as stringers or beams. The second category includes spans with floor-beam systems supported by, or suspended from, one or two large specialized structural members, such as trusses, girders, arches, or cables. Girders and cables are usually made of steel; trusses can be made of steel or timber; and arches can be made of steel, concrete, or masonry. The floor beams are oriented transverse to the centerline of the bridge and either support the deck directly or serve as the end supports for a series of stringerlike sections.

At present, only the stringerlike spans have been implemented in SMART BRIDGE in terms of detailed data entry screens, data storage facilities, and analytical classification procedures. These construction types are the most common for the small bridges likely to be encountered by combat engineers in forward deployment areas. However, rudimentary data entry screens have been implemented for all span construction types, including spans of unspecified construction, so that basic information about any span can be entered.

The eight stringerlike span construction types already implemented are timber stringer, steel stringer, steel stringer with composite concrete deck, reinforced-concrete stringer, reinforced-concrete slab, reinforced-concrete T-beam, reinforced-concrete box-girder, and prestressed-concrete beam. Timber spans can be made of dimensional structural grade timbers, fabricated glue-laminated beams, or natural rough timbers. The spans rarely exceed 20 ft and are simply supported at the ends. Decks are usually made of timber, laid either flat as planks or on edge to form a laminated deck. Laminated decks are either nailed or glued. The deck can be covered with a wearing surface, usually either a layer of asphalt or a timber treadway.

Steel-stringer spans are often made of standard rolled-steel beams, although longer spans (60–120 ft) can use stringers built of welded steel plates. Spans up to 90 ft long can be simply supported at the ends. However, multiple spans can be of continuous construction in which a single stringer extends across several supports, which distributes the induced internal bending moment and reduces the effective length of each span. Continuous steel-stringer spans can extend up to 120 ft. Decks are usually timber or concrete. Concrete decks can be structurally connected with the steel stringers to form composite beams, which effectively increases the bending moment that the stringers can sustain. The wearing surface, if present, can be a layer of asphalt. For a concrete deck with no explicit wearing surface, the top inch of concrete is often considered to be the wearing surface.

Reinforced-concrete stringers or beams are used in simply supported spans up to 60 ft and in continuous-span bridges with clear spans up to 100 ft. Although concrete is well suited to resist compression, embedded-steel-reinforcing rods allow the beams to resist tension. The decks are usually concrete and can be either composite or noncomposite with the beams. Often, a section of the deck is fabricated as an integral part of the reinforced-concrete beam to form a composite T-beam. Placed side by side, the T-beams form both the stringers and the deck. In either case, a wearing surface of asphalt can be added, or the top inch of concrete can be considered to be the wearing surface.

Reinforced-concrete box-girder spans can be as short at 40 ft but are usually 60–160 ft long when used in multiple-span bridges with continuous construction. Whole spans or sections of spans are fabricated as a single unit, with the top serving as the deck and resisting compression, the bottom containing reinforcing steel to resist tension, and the external and internal vertical webs acting as

equivalent beams. Again, a wearing surface of asphalt can be added, or the top inch of concrete can be considered to be the wearing surface.

Reinforced-concrete slabs are usually used for single spans of less than 25 ft. Multiple-span bridges are normally continuous, but span lengths rarely exceed 40 ft. The slab serves as both the structural member and the deck and is generally 8–30 in. thick. A wearing surface of asphalt can be added, or the top inch of concrete can be considered to be the wearing surface and not contribute to the strength of the slab.

Spans using prestressed-concrete beams are similar to spans using reinforced-concrete stringers, except the special embedded steel is placed under tension during beam fabrication. After fabrication, when the tension is released, the beam is naturally under compression. For a well-designed beam, when the beam is incorporated into the span and the span is exposed to the expected vehicular traffic, the compression is reduced to near zero. Consequently, the concrete in the beam never experiences significant tension.

The final information needed about each span is the boundary condition with the next adjoining span, if one exists. The boundary condition can be either simple, indicating that the two spans are separate and independent, or continuous, indicating that the main structural members of the two spans are rigidly and continuously joined at their common support point. Except for span length, none of these parameter values can be changed once the basic record is created.

After values have been entered in all the data fields, the user selects either the Create Bridge and Span Records button to create the basic records or the Cancel button to reject the action. Before the system actually creates the appropriate bridge and span entries in the database, certain consistency checks are performed on the entries. For example, a Bridge ID, a Creator, and a valid Country Code must be present and form a unique key. Also, span lengths must be greater than zero, and spans can have only a continuous boundary condition with adjacent spans of the same construction type. As the basic bridge and span records are created, the system incorporates default values for data fields where defaults are appropriate. If the information is available, the default values depend on the specific country in which the bridge is located. This feature is particularly true of data fields that correspond to the strength of construction materials. Otherwise, general default values are provided.

4.2 ENTERING BRIDGE INFORMATION

Once the basic records are created, the user is presented with a series of bridge information windows, such as the window shown in Figure 2, for entering general information about the bridge. The data fields that make up the database key cannot be edited. The Country of Design entry, if present, is selected from a predefined list. This list includes countries for which specific default

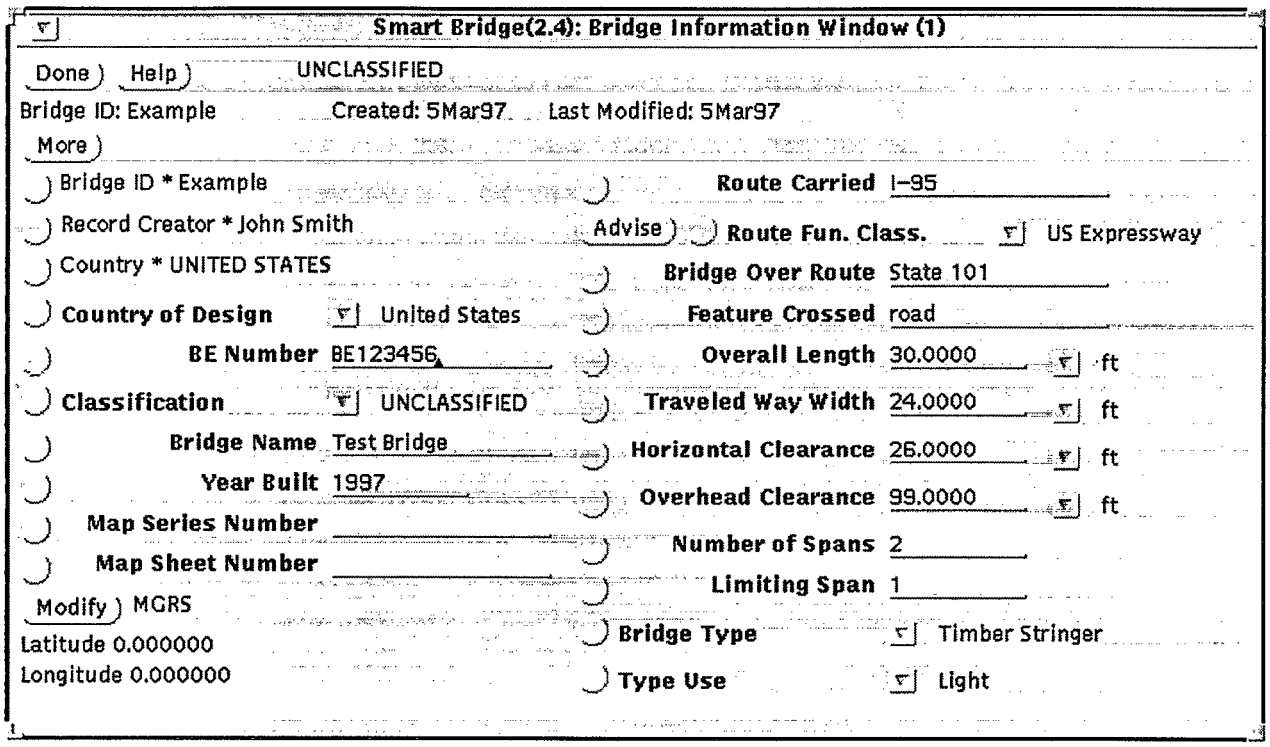

FIGURE 2 Bridge Information Window

values or predefined sets of allowed values for certain data fields exist or for which special classification by correlation procedures have been implemented (Section 6). The Country of Design parameter allows the user to associate a bridge with the design and material standards of a country other than the country in which it is physically located. For example, by using this parameter, the user can treat a bridge in Puerto Rico as if it were designed to the standards used in the continental United States. When appropriate, the default value for this parameter is the country in which the bridge is actually located. The bridge reconnaissance process, described in FM 5-36, *Route Reconnaisance and Classification* (U.S. Army 1985), was used as a guide for determining specific information to be included in a bridge record.

Throughout SMART BRIDGE, each window has a Help button that displays a textual description of the window, its contents, and its purpose. In addition, each data entry field in a window has a small button to its left that brings up an Edit Item window (Figure 3). This window provides a definition of the data item and a means for entering a value. Depending on the data item, the window also explains how the item is to be measured or gathered, discusses typical or default values, and provides access to figures or diagrams that can help the user determine the value of the parameter. The user has a choice of units associated with data items that represent dimensional parameters. This option provides flexibility for using the most appropriate or convenient measurement system.

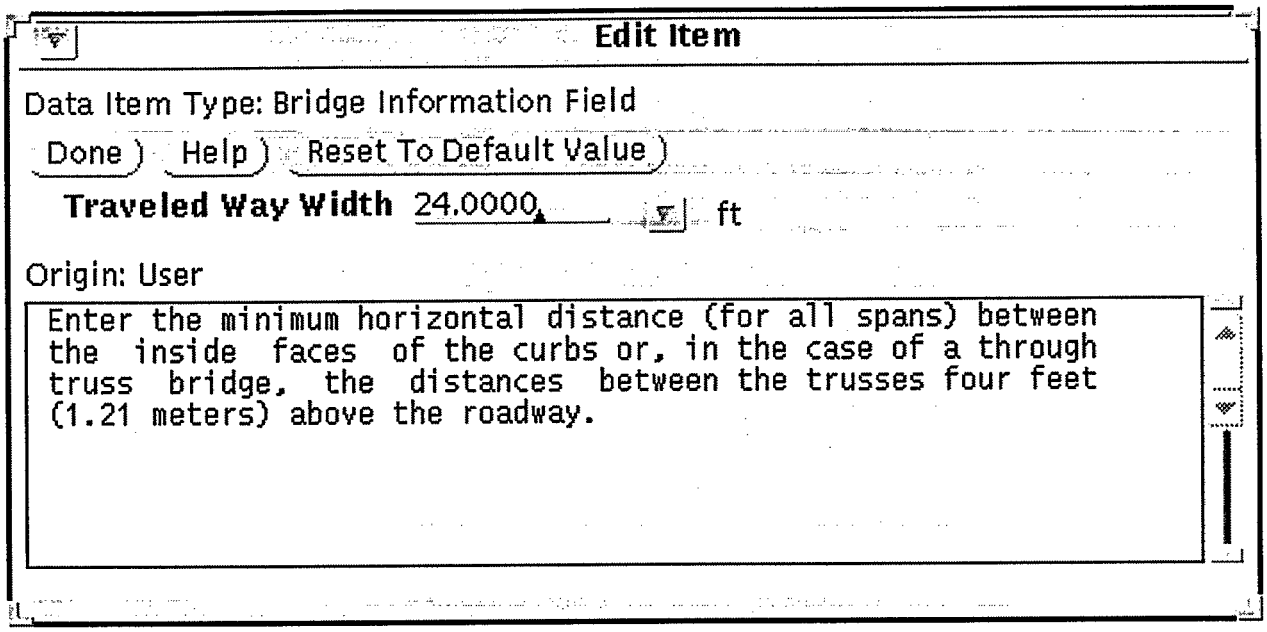

FIGURE 3 Edit Item Window

4.3 ENTERING SPAN INFORMATION

After entering the general information pertaining to the bridge as a whole, the user enters detailed information about individual spans. Upon specifying a particular span, the user is presented with a window that corresponds to that span, such as a timber-stringer span (Figure 4). The exact form of the window depends on the type of construction assigned to the span when the record was created. The user enters information about the span either through a series of span data forms by selecting the Span Info and Span Data Form buttons or through a series of generic span diagrams by selecting the Span Cross Section and Span Side Elevation buttons. Again, the details of the data forms and the generic diagrams depend on the type of construction assigned to the span. In fact, several span construction types use a third diagram that corresponds to a stringer, beam, girder, or slab cross-section. Either approach allows the user to enter values for all the detailed data items needed to fully describe the span. The user selects the more convenient approach under the particular circumstances or, if preferred, a combination of the two approaches.

Figure 5 shows a typical span data form for a timber-stringer span. Again, each window has a Help button; each data entry field has an Edit Item window (Figure 3); and each dimensional parameter has a choice of units. Figure 6 shows a typical generic span diagram for the cross-section of a timber span. The components of the span are labeled, and individual parameters are designated by symbols inside boxes, either within or next to the diagram. Selecting a parameter brings up the Edit Item window for that parameter and provides a definition and a means for entering a value. The color and thickness of the boxes are coded to indicate the source of the present value of the

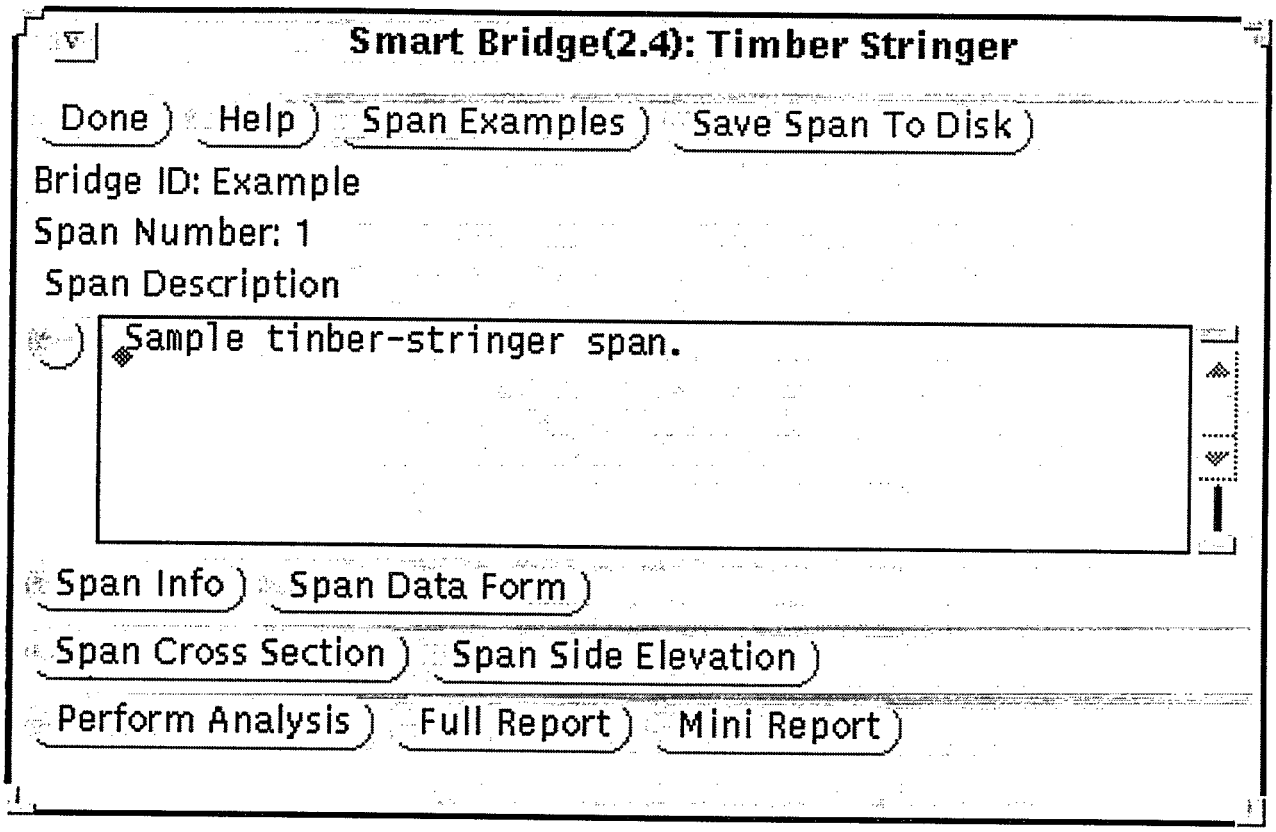

FIGURE 4 Span Window for a Timber-Stringer Span

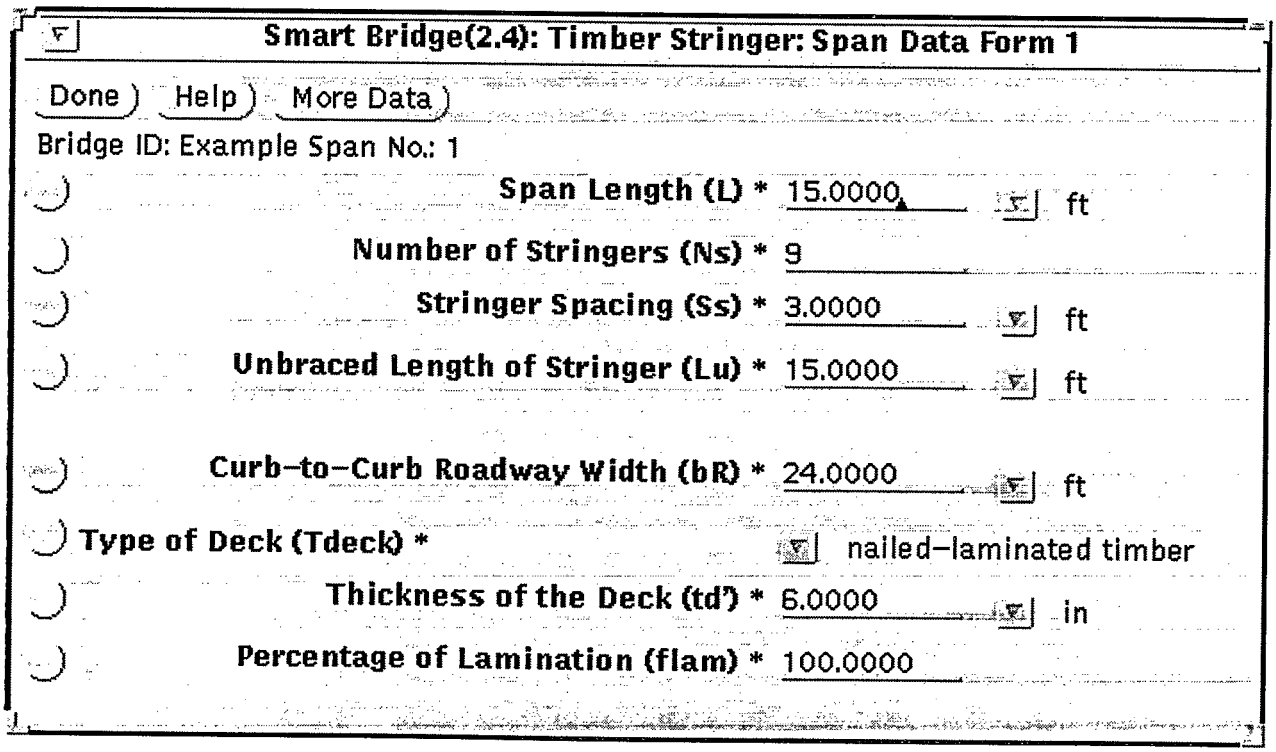

FIGURE 5 Typical Span Data Form

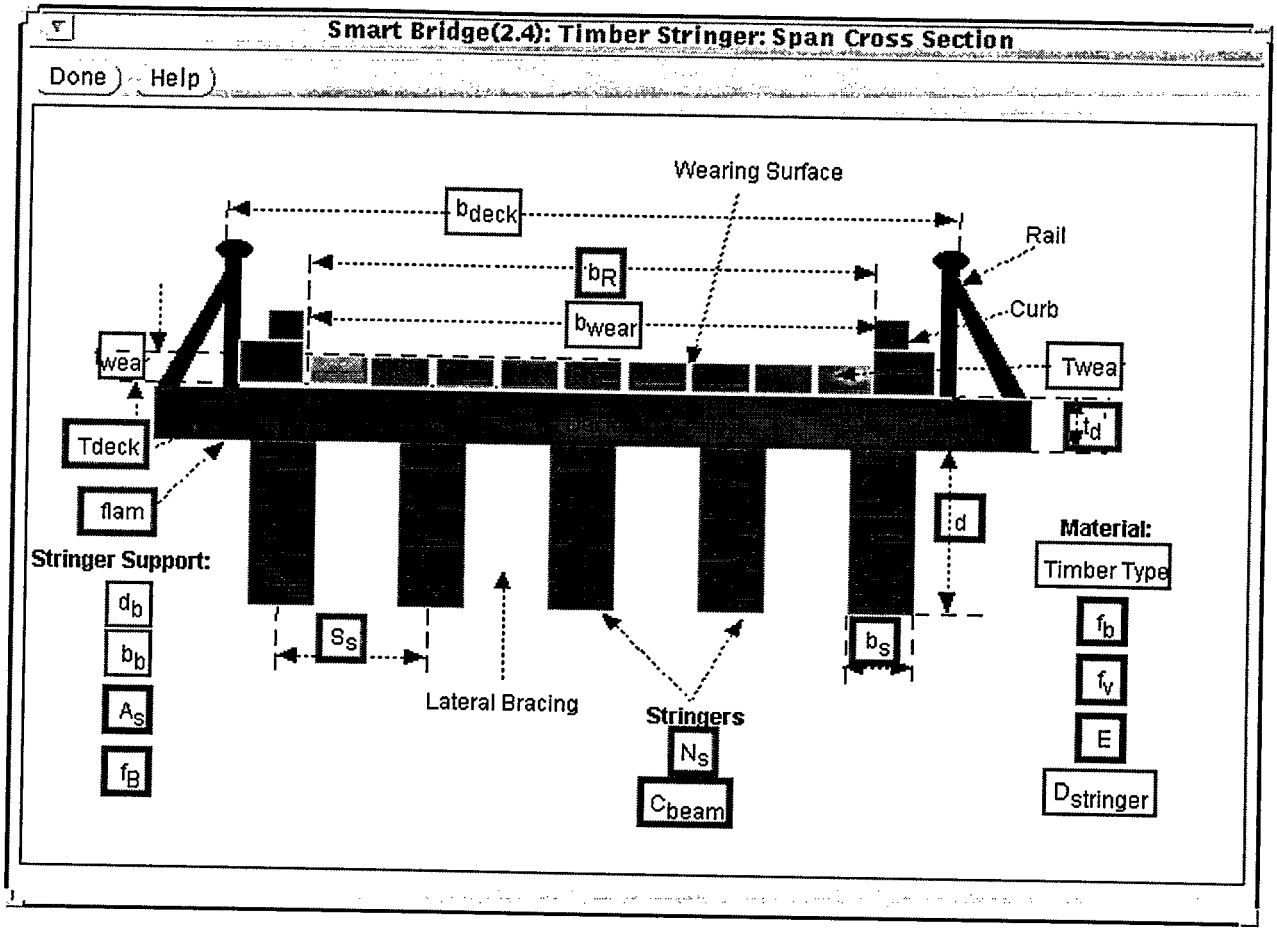

FIGURE 6 Typical Generic Span Diagram

parameter and whether the parameter will be used directly in the detailed analysis of the span. Specifically, a red box indicates that the parameter retains its default value; a green box indicates that the user has specified a value for the parameter; a blue box indicates that the system has automatically calculated a value for the parameter based on the values of other parameters; and a yellow box indicates that a value has been estimated or inferred from the values of other parameters. Parameters whose values are used directly in the detailed analysis of the span are surrounded by boxes with thick boundaries.

During parameter input, the system makes and updates estimates of certain parameter values based on the current values of other parameters. In particular, values for the dead- and live-load continuity coefficients (C_{DL} and C_{LL}) for continuous spans are estimated from the span boundary conditions. Also, the dead-load weight per unit span length of the bridge superstructure (W_{DL}) is calculated from the dimensions of the various components of the superstructure and typical material densities. Bearing or contact areas between stringers and their supports (A_s) are calculated from the dimensions of the contact regions, and stringer cross-sectional areas (A_{beam}) are calculated

from the dimensions of the stringers. For steel stringers, section properties, such as the section modulus (S), the height of the neutral axis (y_{beam}), the effective area of shear (A_v), and the weight per unit length (w_{beam}), are obtained by table lookup for standard rolled shapes or calculated from the dimensions of the stringers. Maximum allowable bending and shear stresses (f_b and f_v) are calculated from the minimum yield stress of the steel used in the construction of the stringers. At any time, if the user can obtain more accurate values for any of these parameters, the estimated or calculated values can be replaced.

4.4 STORING BRIDGE AND SPAN INFORMATION

A set of 12 data tables is used in the SMART BRIDGE databases to store the detailed information about bridges and their spans, including calculated or estimated MLC values. The first 5 tables store information about bridges and spans that is independent of the particular span construction type. However, the remaining 7 tables correspond to the individual implemented span construction types and store information specific to a particular type. Because of the similarity in data requirements for spans constructed with reinforced-concrete beams and prestressed-concrete beams, these construction types share the same data table. The tables and their general contents are listed in Table 1.

Each data item in the database tables has a single-character code that indicates the source of the value stored in that entry. Most items are either entered directly by the user or established by SMART BRIDGE. Items established by SMART BRIDGE are either set as defaults or obtained through table lookup, estimation, inference, correlation, or calculation on the basis of the values of other items. Keeping track of the sources of individual data items in the database and including those sources in the printed reports generated by SMART BRIDGE help the user assess the reliability of any derived quantities, such as MLC values. Data items that represent dimensional quantities, such as length, area, mass, bending moment, stress, or density, also have a two-character code that indicates the unit of measure that accompanies the numerical value. This approach allows the user to enter and store data items in the most convenient unit of measure. SMART BRIDGE converts dimensional parameters to a consistent set of units just before the actual computations are carried out.

TABLE 1 Data Tables Used in the SMART BRIDGE Database

Data Table	Typical Items Stored
BRMASTER	Data items about a bridge that allow quick retrieval of the records for a specific bridge or set of bridges
BRCOMMON	Data items that provide additional general information about the bridge
IMMASTER	File names of images (digitized photographs or sketches), if any, associated with a bridge
SPMASTER	Data items that summarize a span, such as construction type, length, and MLC values
SPCOMMON	Data items common to spans of all construction types, such as deck and wearing surface type, width, and thickness, and roadway width
Span-type specific	Data items specific to spans of a particular construction type, such as the number and dimensions of structural components, the strength of materials, and the weights of components

5 ANALYTICAL CLASSIFICATION

Once the data concerning a bridge and its spans have been entered, the user analyzes each span by selecting the Perform Analysis button on the corresponding span window (Figure 4). When the user selects the analysis option, SMART BRIDGE examines the data associated with the specified span to determine the construction type and the appropriate analytical classification procedure to use. SMART BRIDGE currently has analytical procedures for eight span construction types (Section 4.1). These analytical procedures were derived from the analytical methods described in Section IV of Chapter 3 in FM 5-446. The system can easily incorporate additional procedures for other span types.

A check is then made to determine that values exist for all the attributes or parameters used by the selected analytical procedure. The parameter values are (1) established by the system as default values, (2) entered directly by the user, or (3) calculated by the system from other parameter values. If values are not available for all the needed parameters, the user is alerted to the missing values. The user can then opt either to return to the data entry process (Section 4.3) or to estimate temporary MLC values by using the classification by correlation method described in Section 6, if sufficient information is available.

When it has been determined that values exist for all the parameters used by the analytical procedure, calculations are made to establish MLC values on the basis of one or more of the seven potential limiting factors discussed in Section 2. The specific calculations and the particular limiting factors depend on the span construction type and the analytical procedure being used.

For a timber-stringer span, all seven potential limiting factors are checked. First, the maximum bending moment that an individual stringer can sustain due to the live load of vehicles on the span (m_{LL}) is calculated. This maximum bending moment is such that the allowable bending stress limit for the timber (f_b) is not exceeded within the stringer; the vertical deflection of the stringer will not disrupt the deck (vertical deflection is less than 0.005 times the span length); and the lateral bracing between stringers is sufficient to prevent lateral buckling of the stringers. The maximum live-load bending moments per traffic lane for one- and two-lane operation (M_{LL1} and M_{LL2}) are then calculated by using empirical estimates of the effective number of stringers per lane for one- and two-lane operation (N_1 and N_2). Limiting MLC values based on the bending moment induced in the stringers by wheeled and tracked vehicles in one- and two-lane operation are then evaluated by using M_{LL1} and M_{LL2}, the span length (L), and the tabulated values of live-load bending moments for convoys of the standard military vehicles included in Appendix C of FM 5-446.

The system then calculates the maximum shear force that an individual timber stringer can sustain due to the live load of vehicles on the span (v_{LL}). This force is such that the allowable shear stress limit of the timber (f_v) is not exceeded within the stringer, and the maximum allowable bearing

stress limit of the timber stringer or its supporting material (f_B) is not exceeded. The maximum live-load shear forces per traffic lane for one- and two-lane operation (V_{LL1} and V_{LL2}) are calculated by using empirical estimates of the effective number of stringers per lane (N_1' and N_2'). Limiting MLC values based on the shear force induced in the stringers by wheeled and tracked vehicles are then evaluated by using V_{LL1} and V_{LL2}, the span length (L), and the tabulated values of live-load shear forces for convoys of the standard military vehicles included in Appendix C of FM 5-446.

The system then assigns a limiting MLC value based on the potential for shear failure of the timber deck by using Figure 3-14 of FM 5-446 and also assigns limiting MLC values based on roadway width (b_R) for one- and two-lane operation by using Table 3-3 of FM 5-446. Finally, the system assigns the resulting MLC values for the span for wheeled and tracked vehicles in one- and two-lane operation (a total of four combinations) as the lowest values for the various potential limiting factors. However, for one-lane operation, the width of the roadway is not considered to be a potential limiting factor. Instead, if width would have been the limiting factor for a one-lane bridge, this restriction should be noted and posted at the bridge.

For a steel-stringer span, all seven potential limiting factors are also checked, unless the span has a composite concrete deck. When the deck is composite with the stringers, vertical deflection and lateral buckling are not considered because the composite action of the deck tends to negate these two failure modes. The maximum live-load shear force per traffic lane is assumed to be the same for both one- and two-lane operation (when steel stringers are used) and is estimated using the equivalent of two stringers per lane ($N_1' = N_2' = 2$). Also, for a concrete deck, the system assigns a limiting MLC value based on the strength of the deck using the procedure described in Section 6-10.c of FM 5-446. In applying the procedure, it is assumed that the depth of the reinforcing steel (d_r) is 2 in. less than the actual thickness of the deck (t_d'). Moreover, it is also assumed that the concrete is of a balanced design (the steel and concrete reach their allowable stresses simultaneously) and that the strengths of the steel and concrete are typical of normal construction materials, resulting in a moment capacity per unit length of concrete along the stringers of about 0.214 ksi $\times d_r^2$. This approximate analysis for the moment capacity of a concrete slab is taken from the analysis of a reinforced-concrete slab bridge in Section 5-16 of TM 5-312, *Military Fixed Bridges* (U.S. Army 1968).

For a reinforced-concrete span (either stringer, T-beam, box-girder, or slab), only bending moments that induce excessive bending stresses and roadway width are considered to be potentially limiting factors. Vertical deflection, lateral buckling, and failure due to shear or bearing forces are not likely to be problems in a well-designed, reinforced-concrete structure. First, the system calculates the maximum bending moment that an individual structural element (stringer, beam, girder web, or unit width of slab) can sustain due to the live load of vehicles on the span (m_{LL}). It is assumed that the structural elements are designed so that the reinforcing steel carries all the tension, and the steel will fail in tension before the concrete fails in compression. When calculating m_{LL}, safety factors of 40% and 70% are included in estimating the contributions of the live- and

dead-load bending moments, respectively, to the total bending moment. Also, the total bending moment capacity of each reinforced-concrete element is calculated by using 90% of the yield strength of the reinforcing steel (F_y) as the limiting stress.

As with timber- and steel-stringer spans, the system then calculates the maximum live-load bending moments per traffic lane for one- and two-lane operation (M_{LL1} and M_{LL2}) by using empirical estimates of the effective number of reinforced-concrete elements per lane (N_1 and N_2). For a reinforced-concrete slab span, estimates of the effective slab width per lane for one- and two-lane operation (b_{e1} and b_{e2}) are used. Limiting MLC values are then evaluated based on the maximum live-load bending moments per traffic lane (M_{LL1} and M_{LL2}) and on roadway width (b_R). Finally, the system assigns the resulting MLC values for the span for wheeled and tracked vehicles in one- and two-lane operation (a total of four combinations) as the lowest values for the two potential limiting factors, remembering that roadway width is not considered to be a limiting factor for one-lane operation.

For a prestressed-concrete span, the analysis is similar to that for a reinforced-concrete span. However, the total bending moment capacity of each prestressed-concrete beam is calculated by using either 90% of the estimated allowable stress in the prestressed steel (f_{ps}) or 90% of the 28-day strength of the concrete, depending on the relationship between the strength of the steel and the strength of the concrete.

Upon completion of the span analysis, the user views the MLC values for the span in a pop-up window, along with a brief notation as to what factor, if any, was the limiting factor. At the direction of the user, these MLC values and all the parameter values that describe the span just analyzed can be saved in the span database tables described in Section 4.4. In addition, the system can generate printed reports that summarize the analysis and its results. These reports are described in Section 7.

6 CLASSIFICATION BY CORRELATION

Often, sufficient, detailed information about a bridge is not available for carrying out the analytical classification process described in Section 5. The bridge can be in an area inaccessible to combat engineers, or perhaps it is early in the planning process, meaning that reconnaissance missions have not yet been performed. Therefore, it may be necessary to assign temporary MLC values to a bridge on the basis of available information. One method often used by the military is to correlate the loading generated by hypothetical standard military vehicles with the civilian load configuration for which the bridge was designed or rated. The specific civilian load configuration depends on the organization that regulates roads and highways in the country or region where the bridge is located. Often civilian load configurations are defined in terms of a few standard vehicle configurations that are simplified representations of the largest trucks expected to use the bridge.

6.1 CONCEPT

Except for some timber-stringer bridges and certain short steel-stringer bridges where shear stresses are important and for bridges with narrow roadways, excessive bending stress in structural elements induced by excessive bending moments is usually the factor that limits the MLC values assigned to a bridge. Therefore, correlation between civilian and military loading is generally established in terms of maximum allowable live-load bending moments.

As discussed in Section 2, the maximum allowable total bending moment per structural element (m) depends on the cross-sectional properties of the element and the maximum allowable stress to which the construction material can be safely exposed. The cross-sectional properties of a structural element depend on the dimensions and configuration of the element. Therefore, they depend on the element itself, not on the method of analysis. In contrast, the maximum allowable stress is usually assumed to be some fraction of the strength of the material, and the choice of that fraction is up to the person or organization overseeing the analysis. In general, civilian organizations tend to be more conservative than military organizations in their choice of this fraction because the former usually assumes continual use of the bridge, whereas the latter assumes occasional use. This relationship between the maximum allowable total bending moment used by the military (m_{mil}) and the maximum allowable total bending moment used by civilian organizations (m_{civ}) is expressed as:

$$m_{mil} = \kappa \, m_{civ} \quad . \tag{14}$$

In this relationship, the proportionality factor κ depends on the particular organizations and analyses involved, but typically ranges from 1.3 to 1.5.

Substituting from Equation 5 for both sides of Equation 14 yields:

$$m_{DL} + (1 + I_{mil})\, m_{LLmil} = \kappa\, m_{DL} + \kappa\, (1 + I_{civ})\, m_{LLciv} \quad . \tag{15}$$

The contribution of the dead-load weight of the bridge superstructure to the total bending moment (m_{DL}) is a function of the bridge itself and should not depend on the organization doing the analysis. However, the values used for the impact factors may differ. Solving Equation 15 for the military maximum allowable live-load bending moment per structural element yields:

$$m_{LLmil} = \kappa\, m_{LLciv}\, (1 + I_{civ})/(1 + I_{mil}) + (\kappa - 1)\, m_{DL}/(1 + I_{mil}) \quad . \tag{16}$$

If the second term can be neglected with respect to the first term, Equation 16 can be approximated as:

$$m_{LLmil} \cong \kappa\, m_{LLciv}\, (1 + I_{civ})/(1 + I_{mil}) \quad . \tag{17}$$

This expression for the military maximum allowable live-load bending moment per structural element is conservative because the neglected term is always positive. For the second term to be small, the following must hold:

$$[(\kappa - 1)/\kappa][1/(1 + I_{civ})](m_{DL}/m_{LLciv}) \ll 1 \quad . \tag{18}$$

It is difficult to show that this term is always small. However, when bridges are designed, the contribution of the dead load to the bending moment per structural element (m_{DL}) is deliberately kept as small as possible with respect to the contribution due to the live load (m_{LLciv}). A cursory examination of some actual bridges indicates that the ratio of m_{DL} to m_{LLciv} ranges from 0.1 to 1.0, with 0.5 being typical. By using 1.3 for κ, a conservative value of zero for I_{civ}, and 0.5 for the bending moment ratio, the left side of Equation 18 is 0.12, indicating that the effect of the neglected term is about 12%.

Equation 17 can be put in terms of the maximum allowable live-load bending moments per lane of traffic by multiplying by the effective number of structural elements per lane (Section 2). The latter depends on the particular analysis and the number of lanes of traffic:

$$M_{LL1mil} \cong (N_{1mil}/N_{2civ})\, \kappa\, M_{LL2civ}\, (1 + I_{civ})/(1 + I_{mil}) \quad , \tag{19}$$

and

$$M_{LL2mil} \cong (N_{2mil}/N_{2civ})\, \kappa\, M_{LL2civ}\, (1 + I_{civ})/(1 + I_{mil}) \quad . \tag{20}$$

Because most civilian bridges are designed and rated for two or more lanes of traffic, Equations 19 and 20 are expressed in terms of the civilian maximum allowable bending moment per lane of traffic for two or more lanes of operation (M_{LL2civ}). According to the analytical classification procedures in FM 5-446, N_{1mil} and N_{2mil} depend on the total number of structural elements and the spacing of those elements. It is possible that this information would not be available, unless a person had access to the design drawings or the results of a detailed reconnaissance of the bridge. To proceed with this approach to classification by correlation, one can assume that the two ratios of military-to-civilian effective numbers of structural elements per lane in Equations 19 and 20 are approximated by corresponding ratios that involve only civilian values and that the civilian ratios can be approximated by those suggested by the American Association of State Highway and Transportation Officials (AASHTO 1989); that is,

$$(N_{1mil}/N_{2civ}) \cong (N_{1civ}/N_{2civ}) \cong (K_1/K_2) \quad , \tag{21}$$

and

$$(N_{2mil}/N_{2civ}) \cong (N_{2civ}/N_{2civ}) \cong 1 \quad . \tag{22}$$

Table 2 lists the suggested AASHTO values for the ratio K_1/K_2 in Equation 21 as a function of the type of deck (T_{deck}), the span construction type (T_{span}), and the thickness of the deck (t_d'). If nothing is known about the construction of the bridge, the conservative assumption can be made that there is no advantage to restrict operation to one lane (i.e., assume $K_1/K_2 = 1.0$). The more that is known about the bridge, the more accurately (and less conservatively) the ratio can be determined.

After the additional assumptions involving the number of structural elements per traffic lane (Equations 21 and 22), Equations 19 and 20 become:

$$M_{LL1mil} \cong (K_1/K_2)\ \kappa\ M_{LL2civ}\ (1+ I_{civ})/(1+ I_{mil}) \quad , \tag{23}$$

and

$$M_{LL2mil} \cong \kappa\ M_{LL2civ}\ (1+ I_{civ})/(1+ I_{mil}) \quad . \tag{24}$$

If the civilian design load and the maximum allowable live-load bending moment per lane for a span can be determined, the relationships in Equations 23 and 24 can be used to estimate the military maximum live-load bending moments per lane and thus the MLC values, assuming that the bending moment is the limiting factor. In certain situations, the civilian design standard, or part of it, may be in terms of one lane of traffic or of occasional rather than continual use. For situations

TABLE 2 Ratios of Lateral Distribution Factors Suggested by AASHTO

Type of Deck, T_{deck}	Span Construction Type, T_{span}	Thickness of Deck, t_d' (in.)	K_1/K_2
Simple timber plank	Any	Any	1.07
Multilayer timber plank	Any	≤ 5	1.07
	Any	> 5	1.12
Nailed-laminated timber	Any	< 4	1.07
	Any	≥ 4 and < 6	1.12
	Any	≥ 6	1.18
Glue-laminated timber	Timber-stringer	< 4	1.07
	Timber-stringer	≥ 4 and < 6	1.12
	Timber-stringer	≥ 6	1.20
	Not timber-stringer	< 4	1.07
	Not timber-stringer	≥ 4 and < 6	1.12
	Not timber-stringer	≥ 6	1.17
Concrete	Timber-stringer	Any	1.20
	Steel-stringer, composite steel-concrete stringer, steel girder, truss, prestressed-concrete, suspension	Any	1.27
	Reinforced-concrete T-beam, reinforced-concrete stringer	Any	1.08
	Concrete box-girder	Any	1.14
	Other (including unknown)	Any	1.00
Unknown	Any	Any	1.00

Source: Based on information from AASHTO (1989).

where one lane of traffic is considered in the civilian design standard, relationships analogous to Equations 23 and 24 can be developed in terms of M_{LL1civ}:

$$M_{LL1mil} \cong \kappa \, M_{LL1civ} \, (1 + I_{civ})/(1 + I_{mil}) \quad , \tag{25}$$

and

$$M_{LL2mil} \cong \kappa \, M_{LL1civ} \, (1 + I_{civ})/(1 + I_{mil})/(K_1/K_2) \quad . \tag{26}$$

Where occasional use is considered in the civilian standard, a value of 1.0 is used for κ rather than values like 1.3.

Information concerning civilian design load configurations and civilian treatment of impact loads and allowable stresses is currently included in SMART BRIDGE for the United States, the Republic of Korea (South Korea), and Russia. This information includes tabulated values of the maximum live-load bending moments as a function of span length induced by these civilian design load configurations. SMART BRIDGE can be used to apply the classification by the correlation method described above to bridges in one of these three countries or to bridges designed to the standards established by one of these countries. For example, several South American countries use the same bridge design standards as the United States, just as many countries from the former Soviet Union use Russian bridge design standards. Civilian design considerations for other countries can readily be added as additional correlation procedures are developed.

In the United States, bridges are designed or rated in terms of two hypothetical standard truck configurations (HS and H) established by AASHTO. The HS-type truck is similar to a tractor and semitrailer configuration, but with only three axles. The tractor axles are spaced 14 ft apart, and the trailer axle is from 14 to 30 ft behind the rear tractor axle. The exact spacing of the trailer axle is that which produces the maximum bending moment in the span being designed or rated. The weights on the rear tractor axle and the trailer axle are assumed to be the same, and the weight on the front tractor axle is assumed to be one-fourth that on either of the other two axles. A particular HS truck is designated by a numerical value equal to the sum of the weights on the two tractor axles expressed in short tons. For example, an HS20 truck would have a weight of 4 tons on the front axle, 16 tons on the rear tractor axle, and 16 tons on the trailer axle. Some old, small bridges are designed or rated in terms of an H-type truck. The H truck is similar to a box van with two axles. The axles are spaced 14 ft apart, with the weight on the front axle assumed to be one-fourth of that on the rear axle. A particular H truck is designated by a numerical value equal to the sum of the weights in the two axles expressed in short tons. An H15 truck would have a weight of 3 tons on the front axle and 12 tons on the rear axle. AASHTO (1989) has published tables of live-load bending moments as a function of span length for these two standard truck configurations. The tabulated values are adjusted

for short spans to account for the fact that only a portion of the truck is on the span at any one time and for long spans to account for multiple trucks on the span at the same time.

The Republic of Korea has bridge design standards that are similar to those used in the United States, except that the standard design trucks are designated by DB. A DB truck is defined exactly the same as an HS truck, except that the weight is expressed in metric tons rather than short tons (1 metric ton equals 1.102 short tons). Therefore, a DB-18 truck has a weight of 3.6 metric tons (3.97 short tons) on the front axle, 14.4 metric tons (15.87 short tons) on the rear tractor axle, and 14.4 metric tons (15.87 short tons) on the trailer axle. A bridge designed or rated according to Republic of Korea standards in terms of a DB truck can be classified by the same correlation procedure used for U.S. bridges by converting the DB rating to the equivalent HS rating.

The bridge design criteria used in Russia are slightly more complicated. Both continual use by commercial trucks and occasional use by large special vehicles in one lane are considered. Commercial trucks are represented by the hypothetical standard A-type truck, which has two axles spaced 1.5 m apart, with the total vehicle weight equally distributed between the two axles. Associated with each A truck is a uniform companion load of approximately 0.45% of the total truck weight per meter of span. A particular A truck is designated by a numerical value approximately equal to the weight per axle expressed in tens of kilonewtons (kN). For example, an A11 truck weighs about 220 kN (24.7 short tons) and has a uniform companion load of 1.0 kN/m (68.5 lb/ft). The large special vehicles are represented by the hypothetical HK80 wheeled truck and the hypothetical HG60 tracked vehicle. The HK80 truck has four axles spaced 1.2 m apart, with the total vehicle weight of 800 kN (89.9 short tons) equally distributed among the axles. The HG60 tracked vehicle has two tracks 5.0 m long and a total vehicle weight of 600 kN (67.4 short tons). Two common design situations are often used — one for highways and major roads and one for rural roads. The former includes continual use by pairs of A11 trucks traveling side by side along with their uniform companion loads and occasional use by single HK80 trucks in one-lane operation, whichever has the maximum effect. For rural roads, continual use by pairs of A8 trucks traveling side by side along with their uniform companion loads and occasional use by single HG60 tracked vehicles in one-lane operation are considered. These two design situations are referred to in SMART BRIDGE as A11x2/HK80 and A8x2/HG60, respectively.

6.2 IMPLEMENTATION IN SMART BRIDGE

When the user selects the Perform Analysis button on a span window (Figure 4), SMART BRIDGE examines the data associated with that span to determine its construction type and the appropriate analytical classification procedure. If the span is one of the eight implemented types and values are not available for all the parameters needed to carry out the analytical classification procedure, the user can estimate temporary MLC values by using classification by correlation. If the

span is not one of the eight implemented types, SMART BRIDGE automatically attempts classification by correlation.

For SMART BRIDGE to apply a classification by correlation procedure, the value of the Country of Design parameter for the bridge must be one of the implemented countries (United States, Republic of Korea, or Russia), and a valid value for civilian design load or inventory rating parameter must be present. In addition, values for the span length (L), the span live-load continuity coefficient (C_{LL}), and the curb-to-curb roadway width (b_R) must be present. A conservative value of 1.0 can be entered for C_{LL} if a more appropriate value is not available. Also, because the roadway width is used only to check for limitations due to required lane widths for two-lane operation, the user can enter any nonzero conservative value to check for limitations due to excessive bending stresses. Other span parameters, such as span construction type (T_{span}), type of deck (T_{deck}), and deck thickness (t_d'), can be used to improve the accuracy of a particular correlation procedure; however, only a valid design load or inventory rating and a span length within about 10% of the true value are needed to obtain reasonable results.

The span length can be obtained by direct measurement, from civilian records, or by estimation from remote imagery. If possible, design loads and inventory ratings should be obtained from civilian records. However, if that option is not available, the user may be able to infer the design load of a bridge on the basis of the country or region in which the bridge is located and the functional classification of the route carried by the bridge. The functional classification of a route is a designation of the type of traffic expected to use the route. The responsible organizations in different countries use different systems or schemes to categorize or classify roadways. Usually, countries establish minimum design standards for bridges built along routes of a particular functional classification. While entering bridge information into SMART BRIDGE (Section 4.2), whenever the Country of Design parameter is set or modified, the list of possible values for the Functional Classification of Route Carried (Route Fun. Class.) parameter is revised, and the parameter is set to a default value of Unknown. The user can then assign an appropriate value by selecting from the list. If the correct Functional Classification of Route Carried is not known, the Edit Item window associated with this parameter provides hints on how to infer a value on the basis of the characteristics of the route. Relevant characteristics include age, number of lanes, lane widths, existence and condition of shoulders, access restrictions, speed limits, observed traffic, type of area traversed, and sizes of population centers connected.

In the United States, roadways are classified as expressways, arterials, collectors, and local roads. Bridges on expressways and arterials are usually designed for HS20 trucks, while bridges on collectors and local roads may be designed only for HS15 trucks. When the user assigns one of these four functional classifications to the route carried by a bridge, SMART BRIDGE sets the default value of the Design Load parameter to the corresponding HS truck. The user can change this value if additional information becomes available. Many bridges in the United States are assigned inventory ratings by various state and local governments in accordance with guidance supplied by the Federal

Highway Administration of the U.S. Department of Transportation. The inventory rating is a measure of the carrying capacity of a bridge for normal, continual operation in its present condition expressed in terms of the AASHTO standard vehicles (HS or H). For example, a bridge with an inventory rating of HS24.4 can support HS trucks that have a total gross weight 22% greater than an HS20 truck (43.92 short tons). The inventory rating can be less than or greater than the design load, depending on the condition of the bridge and the conservatism built into the original design. When entering bridge information into SMART BRIDGE, the user inputs a value for the Inventory Rating parameter, if available. Besides the United States, many protectorates and former protectorates of the United States, as well as several South American countries, use this design and rating scheme.

Roadways in the Republic of Korea are classified as expressways, national or provincial roads, and county roads. Bridges on expressways in the Republic of Korea are usually designed for DB-24 trucks. However, the DB-18 truck is used as the design vehicle for bridges on national and provincial roads, while the DB-13.5 truck is used for bridges on county roads. When the user assigns one of these three functional classifications to the route carried by a bridge, SMART BRIDGE sets the default value of the Design Load parameter to the corresponding DB truck. The user can change this value if additional information becomes available.

In Russia and much of the former Soviet Union, roadways are classified as Category IA, IB, and II highways or Category III, IV, and V roads. The design configuration referred to as A11x2/HK80 is used for bridges on highways and major roads designated as Category IA, IB, and II highways and Category III roads. The design configuration referred to as A8x2/HG60 is used for bridges on rural roads designated as Category IV and V roads. When the user assigns one of these six functional classifications to the route carried by a bridge, SMART BRIDGE sets the default value of the Design Load parameter to the corresponding design configuration. The user can change this value if additional information becomes available. Within SMART BRIDGE, if a bridge of Russian design carries somewhat more or less than one of the two common design configurations, a rating factor may be included with the design configuration. For example, a bridge designed or rated as 0.8A11x2/HK80 would be able to carry vehicles of the same axle spacing and weight distribution as those in the A11x2/HK80 design configuration, but weighing 20% less.

When SMART BRIDGE applies a classification by correlation procedure, the value of the Country of Design parameter determines the procedure to be used. The value of either the Inventory Rating parameter or the Design Load parameter forms the basis of the correlation, depending on which parameter contains a valid rating or design format for the procedure. If both parameters contain valid formats, the Inventory Rating is used because it supposedly more closely represents the condition of the bridge as it presently exists.

Similar to a detailed analytical classification, when a planner uses SMART BRIDGE to apply a classification by correlation procedure to a span, the estimated MLC values for the span are

presented in a pop-up window. At the direction of the user, these MLC values are saved in the span database tables (Section 4). In addition, the user can have the system generate printed reports that summarize the correlation process and its results. These reports are described in Section 7.

7 PRINTED REPORTS

SMART BRIDGE is intended to support (1) military engineers in classifying the capacity of bridges for military vehicles and (2) military transportation planners in identifying suitable ground transportation routes. SMART BRIDGE generates two general types of printed reports to provide the appropriate information. When MLC values are assigned to an individual span, a report can be generated that describes the span, the procedure used to arrive at the MLC values, and the resulting MLC values. Two versions of span reports are available. One includes only the essential details, and one adds descriptive material that outlines the classification procedure. The short version of the report is generated by selecting the Mini Report button in the span window (Figure 4) after selecting the Perform Analysis button and completing the analysis. The complete version of the report is generated by selecting the Full Report button. In both cases, the reports are created in PostScript™ format and displayed on the screen using Ghostscript and Ghostview. The user then directs the reports to a printer, if desired.

After all the bridge spans have been evaluated and the results stored in the database managed by SMART BRIDGE, a bridge report can be produced that includes all the information recorded about the bridge and summarizes the characteristics of each span. This report is generated by selecting the Bridge Report button in the initial Bridge Window.

7.1 SPAN REPORTS: ANALYTICAL CLASSIFICATION

When an analytical classification procedure is used to obtain the MLC values for a span, the report describes the span and summarizes the parameter values used in the computations, the computations themselves, intermediate calculated values, and the resulting MLC values. If any of the MLC values are limited (i.e., less than 150), the source of the limitation is noted. In situations where the MLC values are lower than expected, knowledge of the source of the limitation may direct the user to values of parameters that are either incorrect or in need of more careful evaluation.

The report indicates the sources of individual parameter values and other data items. Data items can be either entered directly by the user or established by SMART BRIDGE. Items established by SMART BRIDGE can be either set as defaults or obtained through table lookup, estimation, or calculation on the basis of other items. Keeping track of the sources of individual data items and including those sources in the printed reports helps the user assess the reliability of the assigned MLC values.

The specific contents of the reports depend on the particular analytical procedure. However, all span reports start out by listing data items that identify the bridge to which the span belongs. Included are those items that make up the unique key that identifies the bridge in the database

(Bridge ID, Creator, and Country), along with the name of the bridge, the number of spans, and the Country of Design. The full report then contains textual descriptions of the bridge, the span, the classification method used, and the span classification results. The short or mini report simply identifies the span by number and construction type and the classification method by reference to the appropriate section of FM 5-446.

All the parameters that describe the detailed construction of the span are then listed, along with their mathematical symbols, numerical values, sources, and units, if appropriate. If the user has entered the values of individual dimensional parameters in measurement units other than the standard units used directly by SMART BRIDGE, the equivalent values in the standard units are also included. Typical span parameters, their mathematical symbols, and standard units include:

- Span length L (ft);
- Dead-load continuity coefficient for continuous spans C_{DL};
- Live-load continuity coefficient for continuous spans C_{LL};
- Number of structural elements (stringers, beams, webs) N_s, N_B, N_T, or N_I;
- Structural element spacing S_s, S_B, S_T, or S_I (ft);
- Dimensions and sectional properties of the structural elements, such as width, depth, thickness b, d, and t (in.), section modulus S or S_{beam} (in.^{3}), cross-sectional area A_{beam} (in.^{2}), height of the neutral axis y_{beam} (in.), effective area of shear A_v (in.^{2}), and weight per unit length w_{beam} (lb/ft);
- Cross-sectional area of the reinforcing or prestressed steel per structural element A_{st} (in.^{2} or in.^{2}/ft);
- Location/depth of the reinforcing or prestressed steel d' or d_{st} (in.);
- Dimensions of bearing or contact area between the support material and the structural elements, such as length d_b (in.), width b_b (in.), and area A_s (in.^{2});
- Properties of the materials that make up the structural elements and their supports, such as the yield strength of the steel F_y (ksi), the ultimate strength of the prestressed steel f_{pu} (ksi), the maximum allowable bending stress of the stringer material f_b (ksi), the maximum allowable shear stress of the stringer material f_v (ksi), the maximum allowable concrete stress f_c' (ksi), the modulus

of elasticity of the stringer material E (ksi), and the maximum allowable bearing stress at the stringer support f_B (ksi);

- Lateral brace spacing along the stringers S_b (ft) or unbraced length of the stringers L_u (ft);
- Type of deck T_{deck} (unknown, simple timber plank, multilayered timber plank, nailed-laminated timber, glue-laminated timber, or concrete);
- Thickness of the deck t_d' (in.);
- Curb-to-curb roadway width b_R (ft);
- Dead-load weight of the bridge superstructure per unit length of span W_{DL} (kip/ft); and
- Items used to estimate the dead-load weight, such as the full width of the deck b_{deck} (ft), the type of wearing surface T_{wear} (none, timber, compacted sand or gravel, or asphalt or concrete), the width of the wearing surface b_{wear} (ft), the average thickness of the wearing surface t_{wear} (in.), the number and size of bracing elements, and the average weight of accessories per unit length of span w_{acc} (kip/ft).

Subsequent sections of the report describe each of the applicable potential sources of limitation to the classification of the span — bending stress, shear stress, bearing stress, strength of decking, and width of roadway. For each potential source, the relevant calculations are summarized and the resulting MLC values are listed. In the full printed report, each step in the calculation is described, and the applicable formulas and numerical results presented. The short printed report includes only the formulas and the results. The final section of both span reports summarizes the resulting MLC values from each of the potential sources of limitation and presents the overall span classification results. These results consist of MLC values for wheeled vehicles in one-lane operation, wheeled vehicles in two-lane operation, tracked vehicles in one-lane operation, and tracked vehicles in two-lane operation. Each MLC value that is limited (i.e., less than 150) is accompanied by a phrase that indicates the source of the limitation (bending stress or moment, vertical deflection, lateral buckling, shear stress, bearing stress, roadway width, or strength of decking).

To add to the usefulness of the MLC values assigned to a span by means of the analytical procedures developed by the U.S. Army and incorporated into SMART BRIDGE, the confidence that should be placed in the values needs to be quantified. One approach for establishing a level of confidence is to compare the predictions of the U.S. Army procedures in SMART BRIDGE with the

predictions of well-accepted analytical procedures developed by professional structural engineers. The effort required to complete this comparison for all the bridge construction types included in SMART BRIDGE is beyond the scope of the present project. However, to investigate the approach and demonstrate how the results could be incorporated into SMART BRIDGE, a set of about 90 actual steel-stringer bridges with concrete decks was selected. These bridges are part of the State of Maryland highway system and have been studied in detail by the Bridge Engineering Software (BEST) Center, Department of Civil Engineering, University of Maryland.

The BEST Center used their MERLIN-DASH bridge design and analysis computer code, the definitions of the standard NATO wheeled and tracked vehicles, and a maximum allowable bending stress factor comparable to that used by the military to assign MLC values to each of the 90 bridges. The SMART BRIDGE analytical procedure was also applied to the same bridges. On the average, the two methods agreed quite well. That is, about 50% of the time the SMART BRIDGE MLC values were up to 24% less than the BEST Center values, and about 50% of the time they were up to 34% greater. If it is assumed that the limiting spans of the 90 bridges are typical of similar steel-stringer spans and that the MLC values predicted by the BEST Center closely represent the actual capacities of the spans, the likelihood that the MLC values predicted by SMART BRIDGE will exceed the actual capacity of the span is about 50%. Adjusting the MLC values predicted by SMART BRIDGE downward increases the likelihood that the predictions will not exceed the actual capacity of the span. In the span reports for the analytical classification of steel-stringer spans similar to the 90 bridges studied in terms of span length and capacity, adjusted MLC values corresponding to 90 and 99% likelihoods of not exceeding the actual capacity of the span have been included to guide the user in interpreting the SMART BRIDGE results.

7.2 SPAN REPORTS: CLASSIFICATION BY CORRELATION

When a classification by correlation procedure is used to estimate MLC values for a span, the span report describes the span and summarizes the parameter values used in the correlation, the calculations performed, and the resulting estimated MLC values. The sources of the individual parameter values and other data items are indicated in the report. The user either enters data items directly or allows them to be established by SMART BRIDGE. Items established by SMART BRIDGE can be either set as defaults or estimated or inferred from other items. Again, tracking the sources of individual data items and including those sources in the printed reports helps the user assess the reliability of the estimated MLC values.

The specific contents of the reports depend on the particular correlation procedure used. However, all span reports start out by listing data items that identify the bridge to which the span belongs. These items include those that make up the unique key that identifies the bridge in the database (Bridge ID, Creator, and Country), along with the name of the bridge, the number of spans, and the Country of Design. Items related to the normal civilian characterization of the bridge are then

listed, including the year in which the bridge was built, the functional classification of the route carried by the bridge, the design load for the bridge, the inventory and operating ratings of the bridge, and the gross load limit.

The full report gives written descriptions of the bridge, the span, the correlation procedure used, and the estimated span classification results. The short report simply identifies the span by number and construction type and the correlation procedure by reference to the appropriate civilian design or rating standards.

All the parameters that describe the span and are used in the classification by correlation procedure are then listed, along with their mathematical symbols, numerical values, sources, and units, if appropriate. If the user has entered the value of individual dimensional parameters in measurement units other than the standard units used by SMART BRIDGE, the equivalent values in standard units are also included. The span parameters, their mathematical symbol, and standard units include:

- Decoded inventory rating, design load, or load configuration and rating factor R_f extracted by SMART BRIDGE from the value of the inventory rating or design load parameters;
- Span length L (ft);
- Live-load continuity coefficient in the case of continuous spans C_{LL};
- Curb-to-curb roadway width b_R (ft);
- Span type (unspecified, timber stringer, steel stringer, composite steel concrete, reinforced-concrete stringer, reinforced-concrete slab, reinforced-concrete T-beam, concrete box-girder, prestressed concrete, steel-girder, truss, trussed deck arch, 2 hinge through arch, masonry arch, fixed end arch, and suspension);
- Type of deck T_{deck} (unknown, simple timber plank, multilayered timber plank, nailed-laminated timber, glue-laminated timber, or concrete); and
- Thickness of the deck t_d' (in.).

The subsequent two sections of the report examine the potential sources of limitation to the classification of the span by correlation — bending stress and width of roadway. For bending stress, the relevant calculations are summarized, and the resulting MLC values are listed. The full report describes each step in the calculation and presents the applicable formulas and numerical results. The

short report includes only the formulas and the results. The final section of both span reports summarizes the resulting MLC values from each of the potential sources of limitation and presents the overall span classification results. These results consist of MLC values for wheeled vehicles in one-lane operation, wheeled vehicles in two-lane operation, tracked vehicles in one-lane operation, and tracked vehicles in two-lane operation. Each MLC value that is limited (i.e., less than 150) is accompanied by a phrase that indicates the source of the limitation (bending stress or roadway width).

To add to the usefulness of the MLC values estimated by correlation with civilian design or rating load configurations, the confidence that should be placed in the values needs to be quantified. One major source of uncertainty in applying a classification by correlation procedure is determining the appropriate design or rating load. It would be difficult to quantify that uncertainty in general terms because the design or rating load may be either accurately known from recent civilian records or simply an educated guess. However, even if the design or rating load is precisely known, an intrinsic uncertainty is introduced by the correlation procedure. One method of quantifying this intrinsic uncertainty is to compare the predictions of the correlation method with those of a well-accepted analytical procedure using rating loads for the correlation method calculated by the well-accepted analytical procedure. This method would have to be applied separately to each correlation procedure. At present, the method has been applied only to the correlation procedure for U.S. bridges to demonstrate how the results of such a comparison could be used to quantify confidence in the correlation estimates.

For a set of about 120 bridges in their database of Maryland bridges, the BEST Center assigned MLC values by using the MERLIN-DASH bridge design and analysis computer code (Section 7.1). They also determined rating loads for each of the bridges based on the standard HS truck load configuration established by AASHTO for bridge design and rating in the United States. The correlation procedure in SMART BRIDGE for U.S.-designed bridges was then applied to the same bridges, using those rating loads.

If it is assumed that the limiting spans of the 120 bridges are typical of similar spans in the United States and that the MLC values predicted by the BEST Center closely represent the actual capacities of the spans, the likelihood is about 90% that the MLC values predicted by correlation will not exceed the actual capacity of the span if the design or rating load is precisely known. Adjusting the MLC values predicted by correlation downward increases the likelihood that the predictions will not exceed the actual capacity of the span. These conclusions are included in the SMART BRIDGE span reports for the classification by correlation of U.S.-designed spans (and, by extension, the Republic of Korea) similar to the 120 bridges studied in terms of span length and capacity to guide the user in interpreting the correlation results.

7.3 BRIDGE REPORTS

After analyzing all the spans that make up a bridge, the user can direct the system to assign MLC values to the bridge as a whole by selecting the smallest values from among all the spans that make up the bridge. Again at the direction of the user, these bridge MLC values can be saved in the bridge database tables described in Section 4.4. In addition, the user can have the system generate a report that describes the bridge and summarizes the characteristics of each span.

The bridge report supplies all the particulars that might be needed by a transportation planner. The report lists data items that identify the bridge and the origin of the information. These items include those that make up the unique key that identifies the bridge record in the SMART BRIDGE database (Bridge ID, Creator, and Country), along with the name of the bridge, the year it was built, its location, the date the record was first created, the date the record was last modified, and a description of the origin of the information about the bridge. The location of the bridge is expressed in terms of latitude and longitude but can include coordinates in terms of the Military Grid Reference System and references to standard military map series and map sheet numbers.

The general characteristics of the bridge are then listed, followed by the assigned MLC values for wheeled and tracked vehicles in one- and two-lane operation. The general bridge characteristics include:

- Bridge Type (construction type of main span),
- Overall Length of Bridge,
- Roadway Route Carried by Bridge,
- Country of Design (if known),
- Functional Classification of Route Carried (if Country of Design is designated),
- Design Load,
- Operating Rating,
- Inventory Rating,
- Gross Load Limit,
- Feature Crossed by Bridge,

- Roadway Route Crossed by Bridge (if any),
- Number of Spans,
- Limiting or Controlling Span,
- Type of Use (heavy, medium, light, or unknown), and
- Bridge Bypass Conditions (unknown, easy, difficult, or impossible).

The report then includes any descriptions of qualifications and limitations pertaining to the assigned MLC values and the condition of the bridge substructure and superstructure. Relevant bridge clearances are specified in terms of traveled way width (between curbs), horizontal clearance (above curbs), and overhead clearance, and the approaches to the bridge are characterized by minimum roadway width, roadway surface, maximum grade, and minimum curvature.

Each span is then individually summarized in terms of MLC values, a textual description, and general characteristics. The general span characteristics include:

- Span Type (construction type),
- Span Length,
- Boundary Condition at West/North End (simple or continuous),
- Boundary Condition at East/South End (simple or continuous),
- Curb-to-Curb Roadway Width,
- Type of Deck (unknown, simple timber plank, multilayered timber plank, nailed-laminated timber, glue-laminated timber, or concrete)
- Type of Wearing Surface (none, timber, compacted sand or gravel, or asphalt or concrete),
- Is Span Usable? (yes or no),
- Is Span Movable? (yes or no),
- Is Span over Water? (yes or no),

- Clear Distance above Normal Water Surface (if over water),
- Clear Distance above Stream Bed (if over water), and
- Clear Distance above Ground Surface (if not over water).

As with the span reports, the sources of individual items are indicated in the report. The user enters most items directly or accepts values established by SMART BRIDGE. Values established by SMART BRIDGE can be either set as defaults or obtained through table lookup, estimation, inference, correlation, or calculation on the basis of other items.

8 SUMMARY AND CONCLUSIONS

SMART BRIDGE is a usable initial step in developing a tool to assist (1) military engineers in classifying existing bridges in terms of their military capacity and (2) military transportation planners in identifying potential limitations to ground transportation routes. The system captures the knowledge of what attributes of a bridge are important for classification and transportation planning. Input screens, on-line help documents and diagrams, and automated links among parameters help the user acquire the needed information about a bridge and establish reasonable values for parameters required for classification that cannot be directly measured. In addition, the system establishes a database framework for collecting, storing, assembling, and retrieving detailed bridge information and analysis results.

Detailed analytical procedures for classifying about half of the bridge construction types considered in FM 5-446 are incorporated into SMART BRIDGE, along with all supporting tabular data and ancillary calculations needed to apply them. This automated process eliminates the tedium involved in applying the procedures, provides the user with printed documentation of the calculations made, and reduces the likelihood of arithmetic and other human errors. Analytical procedures for other bridge construction types can easily be added to extend the usefulness of the system.

The inclusion of classification by correlation procedures for bridges designed or rated according to the standards of certain countries allows users to obtain reasonable estimates of bridge capacities on the basis of very little detailed information. Built-in rules for inferring the design standards of a bridge from the characteristics of the roadway carried by the bridge allow transportation planners to estimate bridge capacities for preliminary planning. New correlation procedures and inference rules for other countries can be added to the system as they are developed.

The two types of bridge classification procedures in SMART BRIDGE essentially represent the extremes. The analytical classification procedures require knowledge of 25 to 35 individual parameters that describe the structural components of a bridge, while the classification by correlation procedures requires knowledge of only 3 or 4 characteristics of a bridge. It is reasonable to assume that the more that is known about a bridge, the more likely it is that the estimated MLC values represent the actual maximum capacity of the bridge. That is, it should be possible to obtain improved estimates of bridge capacity even if only a subset of the 25 to 35 parameter values is known. As SMART BRIDGE matures, two concepts should be explored: (1) estimating bridge capacities on the basis of whatever information is available and (2) estimating the confidence in those capacities based on the quantity and quality of the information.

One approach would be to infer missing parameter values from other known parameter values or bridge characteristics. As the SMART BRIDGE database becomes more populated, artificial

intelligence concepts, such as data mining, case-based reasoning, and neural networks, could be used to search the database and identify rules or trends that could help to estimate missing parameter values and to quantify the expected accuracy of those estimates. Having the capability to estimate the capacities of bridges on the basis of available information rather than having to rely on detailed on-site reconnaissance, which can be expensive or impossible to obtain, would greatly benefit military transportation planners.

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