RULE-BASED DIAGNOSIS OF FAILURE EVENTS

Fabian C. Hadipriono and Chin-Leong Lim

Department of Civil Engineering
The Ohio State University
Columbus, Ohio 43210, USA

INTRODUCTION

When a structural failure occurs, an investigator will observe any signs or warning that may lead to the causes of said failure. As an expert, the investigator will observe the most probable triggering and/or enabling events experienced by each component of the building. A previous paper [2] identifies the enabling events as deficiencies in design and construction, while the triggering events are external causes precipitating the failure. The term "failure" refers to both collapse or distress and is defined as the incapacity of a component to perform as specified in the design and construction requirements.

Despite the role of structural analyses during the investigation, the expert's subjective judgment may play a significant part in determining these events, particularly, when construction errors are involved. However, experience shows that many investigations of the causes of failures often produce controversial results due to the difficulties in tracing the enabling and triggering events. In many cases, assessments become difficult due to the lack of data or the limited experience of the assessor. Therefore, the objective of this paper is to introduce the development of a rule-based expert system for diagnosing construction events that contribute to the failure of a structural component.

To determine the enabling and triggering events the expert system developed for this study incorporates both quantitative analysis based on the information obtained from the failed component and the judgment of experts. Often, more than one event contributes to the failure. The study results in a system that could determine the types of events, including their importance, that contribute to a failed component. The system can be used by someone having little knowledge about failures. A simply supported reinforced concrete beam is selected for this purpose (Figure 1).

FAILURE DIAGNOSIS EXPERT SYSTEM

In this study, a Failure Diagnosis Expert System (FDES) was developed for use in micro computers. The system is designed to allow interactions with the user. Linguistic values are used by the experts when developing the rules to indicate the subjective uncertainties involved in the antecedents or consequent. FDES uses an expert system shell, EXSYS [4], whose function is to perform the inferencing on the production rules that are input into the knowledge base of the shell. EXSYS has its own editor for the user to construct the rules. The run-time and the work file consisting of the knowledge base are the softwares that can be used by a user for investigating the causes and their importance.

In order to facilitate access during inferencing, the knowledge structure of the system is divided into three levels. The first level determines the type and extent of failure. Only two types of failure are considered here: flexural and shear. The second level is the intermediate step that connects the failure condition with the enabling and triggering events. The third level diagnoses the type of these events. These levels are illustrated in Figure 2.

The knowledge base includes information gathered from experts in terms of IF-THEN statements or production rules. This information, concerning the type and causes of the component failure, are assessed based on facts and heuristics and are organized to become the production rules. A production rule is a set of IF-THEN statements that describe the conditions which are required to satisfy the occurrence of an event. The IF statements (conditions) are usually called the "antecedents," while the THEN statements are the "consequents." In the knowledge base tree structure, a consequent of a production rule can be used as the antecedent of the rules in the next level of the tree structure. These latter rules are the intermediate rules whose consequent can again be used as the antecedent of the rules that follow.

In addition, all the rules developed for this paper always contain conjunction clauses in the antecedents. In other words, all antecedents or consequents are connected through a conjunction term AND. All disjunction clauses in the antecedents are separated into conjunction clauses; hence, the term OR is not used to connect the antecedents. The following is an example of a rule that determines the type of failure:

IF Actual Moment Resistance is less than Actual Moment Load
AND 1.05*(Actual Moment Resistance) is greater than Actual Moment Load
AND Actual Moment Resistance is less than Specified Moment Resistance
AND Specified Moment Resistance is greater than or equal to Actual Moment Load

THEN There is a LOW possibility of the occurrence of flexural failure due to construction error

Note that when developing this rule, the expert uses a linguistic value "LOW" to indicate the subjective uncertainty of flexural failure due to a construction error. This value is related to the 5% variability of the Actual Moment Resistance.

The above consequent may be followed by this rule:

IF There is a LOW possibility of the occurrence of flexural failure due to construction error
AND Variability of the constructed beam effective depth is SMALL

THEN There is a FAIR possibility that failure is caused by error in beam effective depth during construction.

Note that the first antecedent in the second rule is used to relate the two rules for obtaining the final conclusion. The second antecedent can be obtained from the following rule:

IF actual beam effective depth is less than the specified effective depth
AND actual beam effective depth is greater than 95% of the specified effective depth

THEN variability of the constructed beam effective depth is SMALL

In the first rule, observations on the load-resistance relations are required to determine the type of failure. Hence, the actual and specified moment resistance and load should be computed and input into the system.

COMPUTATION MECHANISMS

FDES computes and stores various computations for the load-resistance relations. The effects of concentrated or uniform loads on the beam result in the moment computed using the following equations:

$$\rho_b = \frac{0.85 \times fc \times \beta}{fy} \times \frac{0.003 \times Es}{0.003 \times Es + fy} \quad \ldots\ldots (1)$$

$$\rho = \frac{As}{b \times d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where

ρ_b is the reinforcement ratio that produces balance strain condition

ρ is ratio of the area of tension reinforcement to the concrete
fc is concrete compressive strength
fy is rebar yield strength
β is 0.85 as in section 10.2.7.3 ACI code [1]
Es is the rebar modulus of elasticity
As is the rebar area
b is the beam width
d is the beam effective depth

If $\rho_b > \rho$ then the ultimate moment yields

$$Mu = As \times fy \left(d - 0.59 \frac{As \times fy}{fc \times b}\right) \quad \ldots\ldots\ldots\ldots\ldots\ (3)$$

Else,

$$Mu = 0.85 \times fc \times a \times b \,(d - 0.5 \times a) \quad \ldots\ldots\ldots\ldots\ldots\ (4)$$

where a is found using the following equation:

$$\left(\frac{0.85 \times fc}{0.003 \times Es \times \rho}\right) a^2 + a \times d - \beta \times d^2 = 0 \quad \ldots\ldots\ldots\ (5)$$

Assuming that No. 3 stirrups will be used (area of 0.11 square inches and yield strength of 40,000 psi), the actual and the specified shear strengths are also calculated using the following equations [1]:

$$Vn = Vc + Vs \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

$$Vc = 2\sqrt{fc \times b \times d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

$$Vs = \frac{0.11 \times 40{,}000 \times d}{Sp} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (8)$$

where Vn is nominal shear strength
Vc is nominal concrete shear strength
Vs is nominal steel shear strength
Sp is the stirrup spacing

Equations 1 through 8 are written as a simple external program using BASIC. The program is written in an interactive mode to accomodate information provided by a user.

USER'S INFORMATION

Usually in the aftermath of a failure occurrence, an investigator collects pertinent information about the failed component, such as component properties and geometry (obtained from measurement or test results), the loading conditions, and the appearance of the component (usually obtained from visual inspection).

In this paper, the concrete beam properties are concrete compressive strength, concrete modulus of elasticity, and rebar yield strength. The beam geometry includes the beam length, width, height, effective depth, and rebar area. Since this study is only concerned with construction errors, enabling events related to structural design error are not considered, and we assume that a correct design procedure is performed. Clearly, the knowledge base can be expanded by incorporating such errors. Here, a construction error is defined as the departure of the component properties and geometry from the specifications. An example of a construction error is the reduced effective depth of the beam when not constructed according to specifications. Another example is the reduction of the rebar area due to corrosion or to the selection of improper size of the rebars during construction. The most frequent test performed after a failure is the compressive strength of the concrete. A frequent problem related to this test is the departure of the concrete compressive strength from the specification caused by error in mixing, transporting, consolidating, or curing of concrete.

The loading conditions in this study include the actual uniform and concentrated loads. The uniform loads are the live and dead loads, while the concentrated load is assumed to be in the midspan. Besides the loading conditions, an investigator needs to consider the physical appearance of the failed component when determining causes of a failure. A failed component can be classified in terms of deformation and/or separation. Deformation is exemplified by deflection or displacement of the beam, partially or totally. Separations include cracks and crushing of the concrete. Papers concerning damage assessment of structural components based on physical appearance are presented in References [3,5]. Based upon this visual appearance, an investigator can form his/her opinion regarding the causes of the collapse or distress. For example, cracks in the midspan at the bottom part of a concrete beam may indicate possible flexural failure of the beam.

EXAMPLE

FDES was developed through interactive processes where a user inputs information regarding the component properties and appearance, and the system then provides the consequents and the conclusions of the causes of failure and the extent of said causes. An example of how the system works is presented here. A step-by-step procedure illustrating the rules in the order of appearance is given as shown in Figure 3. The final conclusion, however, can also be reached without going through all these rules. Table 1 provides the variables and descriptions used in FDES.

To begin with, a user will be asked if there is a uniform live load and/or concentrated load using the true/false statement (see Figure 3). Note that the answers given by the user are provided in italics. Suppose that the answers are true; subsequently, rules numbered 5, 1, and 2 will appear on the screen, showing the computations of the moment and shear of the beam. More input on the beam span and magnitude of loads produces rule 34, indicating the possibility of flexural failure due to construction error. Then the user can input information on the actual and specified widths of the beam to obtain the variability of the beam width (rule 7). The same procedure can be used to obtain the variability of concrete strength (rule 12). Rule 150 appears when the input for the amount of concrete crushing is medium. In this example, the rule indicates a fair possibility of failure caused by error in concrete strength. Based upon the input on beam actual and effective depths, the variability of rebar yield strength is shown through rule 21. This rule is followed by rule 176, indicating a high possibility that the construction error is related to the beam effective depth.

Next, information on the actual and specified rebar area produces the variation in the rebar area (rule 23). This rule is followed by rule 49, showing high possibility for shear failure due to overloading and construction error. Information related to the extent of cracks at the ends of the beam leads to rule 125, indicating a high possibility that the overloading is related to the excessive uniform and concentrated loads. More data on the actual and specified stirrup spacings yields the variation in said spacing. Finally, all of this information reveals fair and high possibilities of failure caused by the enabling events (errors in concrete strength and beam effective depth, respectively) and a high possibility of the occurrence of the triggering events (uniform and concentrated loads). The use of the linguistic values is beneficial for the user to determine the rank of importance of the failure events. In this example, error related to the beam effective depth (the enabling event) and excessive uniform and concentrated loads (the triggering event) are the most important events that caused the failure.

The above procedure allows the user to see the stages and the rules required to reach the conclusion. However, FDES also allows the user to simply list all the above information (see Figure 4) and run the program to immediately reach the conclusion. Any modification of the information can also be accomodated in the list to determine a new conclusion.

SUMMARY AND CONCLUSION

The study in this paper is concerned with the development of a modest KBES, the first step towards a more refined work for determining the causes of failure in a structural component. An example, using an expert system shell (EXSYS), demonstrates the use of the FDES to determine the causes of failure and the extent of the failure events in terms of linguistic values. This system can be used on a step-by-step basis such that a user could follow the rules related to the information he/she inputs. One can also reach the conclusion by simply listing all the information and running the system. If the conclusion indicates that more than one event caused the failure, then the most probable event(s) can be found from the extent of said event(s).

The scope of this study is limited to construction problems. A simply supported concrete beam was used for the purpose of this study. Only shear and flexural mode of failures are considered here. The FDES under discussion is still the subject of considerable research which will be presented as it evolves.

REFERENCES

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4. Huntington, D., EXSYS, Expert System Development Package, EXSYS Inc., Albuquerque, New Mexico, NM 87194, 1985.

5. Ross, T.J. and Hadipriono, F.C., "Fuzzy Production Rules for a Damage Assessment Expert System," International Symposium on Fuzzy Systems and Knowledge Engineering, Guangshou, China, 1987.

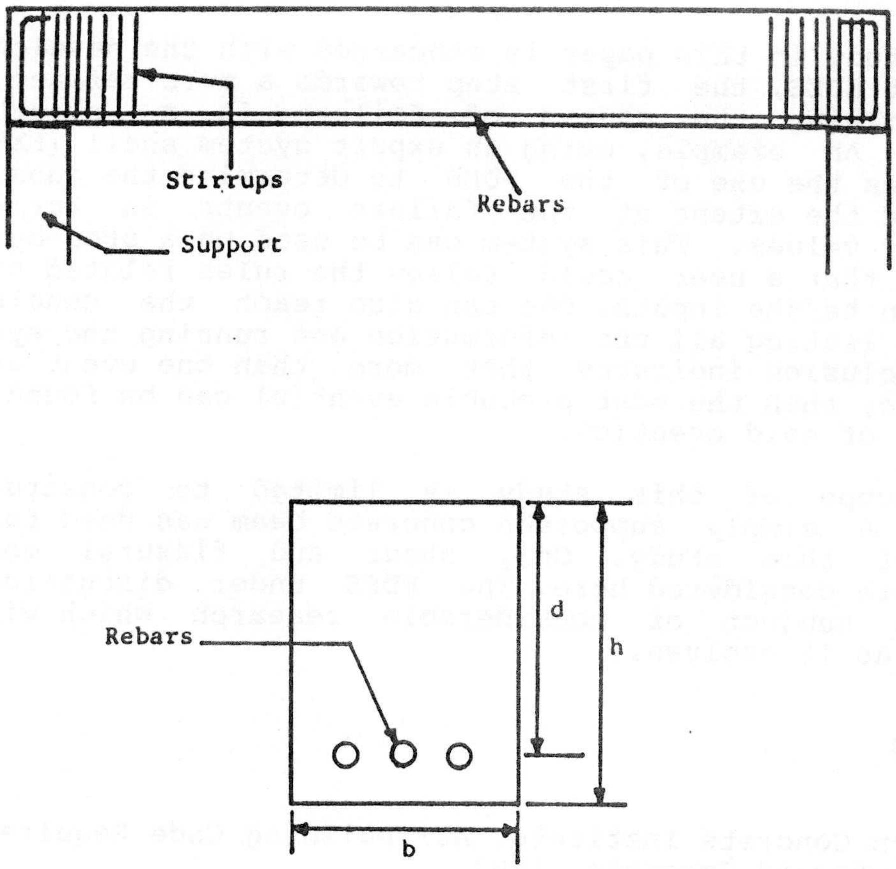

Figure 1. A Simply Supported Reinforced Concrete Beam

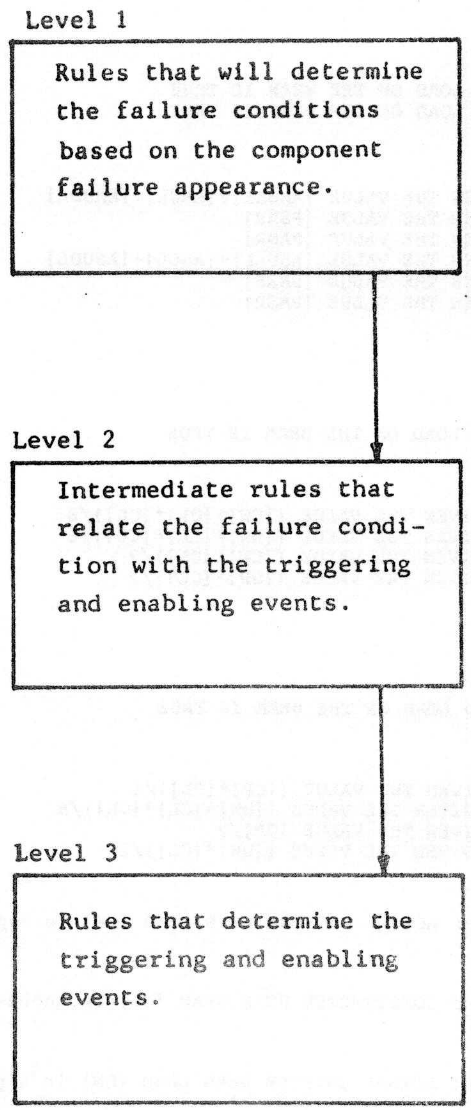

Figure 2. Knowledge Structure diagram

```
UNIFORM LIVE LOAD ON THE BEAM IS
      1    TRUE
      2    NOT TRUE
   1


CONCENTRATED LOAD ON THE BEAM IS
      1    TRUE
      2    NOT TRUE
   1


RULE NUMBER: 5
IF:

      (1)     UNIFORM LIVE LOAD ON THE BEAM IS TRUE
and   (2)     CONCENTRATED LOAD ON THE BEAM IS TRUE

THEN:

              [AML] IS GIVEN THE VALUE [AMULL]+[AMCL]+[AMUDL]
 and          [SMR] IS GIVEN THE VALUE [PSMR]
 and          [AMR] IS GIVEN THE VALUE [PAMR]
 and          [ASL] IS GIVEN THE VALUE [ASULL]+[ASCL]+[ASUDL]
 and          [SSR] IS GIVEN THE VALUE [PSSR]
 and          [ASR] IS GIVEN THE VALUE [PASR]


RULE NUMBER: 1
IF:

      (1)     UNIFORM LIVE LOAD ON THE BEAM IS TRUE

THEN:

              [AMULL] IS GIVEN THE VALUE ([CW]*[CL]*[CL])/8
 and          [AMUDL] IS GIVEN THE VALUE ([DW]*[CL]*[CL])/8
 and          [ASULL] IS GIVEN THE VALUE ([CW]*[CL])/2
 and          [ASUDL] IS GIVEN THE VALUE ([DW]*[CL])/2


RULE NUMBER: 2
IF:

      (1)     CONCENTRATED LOAD ON THE BEAM IS TRUE

THEN:

              [AMCL] IS GIVEN THE VALUE ([CP]*[CL])/4
 and          [AMUDL] IS GIVEN THE VALUE ([DW]*[CL]*[CL])/8
 and          [ASCL] IS GIVEN THE VALUE [CP]/2
 and          [ASUDL] IS GIVEN THE VALUE ([DW]*[CL])/2


Please input the value of ACTUAL UNIFORM LIVE LOAD [CW] in kips/in
Value: 0.5

Please input the value of CONSTRUCTED BEAM SPAN [CL] in inches
Value: 240

Please input the value of ACTUAL UNIFORM DEAD LOAD [DW] in kips/in
Value: 0.07

Please input the value of CONCENTRATED LOAD AT CENTER [CP] in kips
Value: 15


RULE NUMBER: 34
IF:

      (1)     [AMR] < [AML]
and   (2)     [AMR]*1.05 > [AML]
and   (3)     [AMR] < [SMR]
and   (4)     [SMR] >= [AML]

THEN:

              POSSIBILITY OF FLEXURAL FAILURE DUE TO OVERLOAD IS  NONE
 and          POSSIBILITY OF FLEXURAL FAILURE DUE TO CONSTRUCTION ERROR IS LOW
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Figure 3. An Example of FDES

```
Please input the value of ACTUAL BEAM WIDTH [AWIDTH] in inches
Value: 12

Please input the value of SPECIFIED BEAM WIDTH [SWIDTH] in inches
Value: 12

RULE NUMBER: 7
IF:

     (1)     [AWIDTH] >= [SWIDTH]

THEN:

             VARIATION IN BEAM WIDTH IS NONE


Please input the value of ACTUAL CONCRETE STRENGTH [ACONCST] in psi
Value: 3900

Please input the value of SPECIFIED CONCRETE STRENGTH [SCONCST] in psi
Value: 4000

RULE NUMBER: 12
IF:

     (1)     [ACONCST] < [SCONCST]
and  (2)     [ACONCST] > 0.95*[SCONCST]

THEN:

             VARIATION IN CONCRETE STRENGTH IS SMALL


AMOUNT OF CRUSHING OF CONCRETE AT CENTER TOP IS
     1    LARGE
     2    MEDIUM
     3    SMALL
     4    NONE
 2

RULE NUMBER: 150
IF:

     (1)     POSSIBILITY OF FLEXURAL FAILURE DUE TO CONSTRUCTION ERROR
             IS LOW
and  (2)     VARIATION IN CONCRETE STRENGTH IS SMALL
and  (3)     AMOUNT OF CRUSHING OF CONCRETE AT CENTER TOP IS MEDIUM

THEN:

             FAIR POSSIBILITY OF FAILURE CAUSED BY ERROR IN
             CONCRETE STRENGTH

Please input the value of ACTUAL REBAR STRENGTH [AREBARST] in psi
Value: 60000

Please input the value of SPECIFIED REBAR STRENGTH [SREBARST] in psi
Value: 60000

RULE NUMBER: 15
IF:

     (1)     [AREBARST] >= [SREBARST]

THEN:

             VARIATION IN REBAR YIELD STRENGTH IS NONE
```

Figure 3. Cont'd

```
Please input the value of ACTUAL BEAM EFFECTIVE DEPTH [AREBARDP] in inch.
Value: 18

Please input the value of SPECIFIED BEAM EFFECTIVE DEPTH [SREBARDP] in inch
Value: 20

RULE NUMBER: 21
IF:

     (1)    [AREBARDP] < 0.95*[SREBARDP]
and  (2)    [AREBARDP] > 0.85*[SREBARDP]

THEN:

            VARIATION IN BEAM EFFECTIVE DEPTH IS MODERATE

RULE NUMBER: 176
IF:

     (1)    POSSIBILITY OF FLEXURAL FAILURE DUE TO CONSTRUCTION ERROR
            IS LOW
and  (2)    VARIATION IN BEAM EFFECTIVE DEPTH IS MODERATE

THEN:

            HIGH POSSIBILITY OF FAILURE CAUSED BY ERROR IN
            BEAM EFFECTIVE DEPTH

Please input the value of ACTUAL REBAR AREA [AREBARAR] in inch. sq.
Value: 6

Please input the value of SPECIFIED REBAR AREA [SREBARAR] in inch. sq.
Value: 6

RULE NUMBER: 23
IF:

     (1)    [AREBARAR] >= [SREBARAR]

THEN:

            VARIATION IN REBAR CROSS-SECTION AREA IS NONE

RULE NUMBER: 49
IF:

     (1)    [ASR]*1.15 < [ASL]
and  (2)    [ASR] < [SSR]
and  (3)    [SSR] < [ASL]

THEN:

            POSSIBILITY OF SHEAR FAILURE DUE TO OVERLOAD IS HIGH
 and        POSSIBILITY OF SHEAR FAILURE DUE TO CONSTRUCTION ERROR IS HIGH

AMOUNT OF AVERAGE CRACKS SIZE AT ENDS IS
     1   LARGE
     2   MEDIUM
     3   SMALL
     4   NONE
  2

RULE NUMBER: 125
IF:

     (1)    POSSIBILITY OF SHEAR FAILURE DUE TO OVERLOAD IS HIGH
and  (2)    UNIFORM LIVE LOAD ON THE BEAM IS TRUE
and  (3)    CONCENTRATED LOAD ON THE BEAM IS TRUE
and  (4)    AMOUNT OF AVERAGE CRACKS SIZE AT ENDS IS  MEDIUM

THEN:

            HIGH POSSIBILITY OF FAILURE CAUSED BY VERTICAL UNIFORM LIVE LOAD
            AND VERTICAL CONCENTRATED LOAD
```

Figure 3. Cont'd

```
Please input the value of ACTUAL STIRRUP SPACING [ASTRSP] in inches
Value:  4


Please input the value of SPECIFIED STIRRUP SPACING [SSTRSP] in inches
Value:  4


RULE NUMBER: 27
IF:

     (1)    [SSTRSP] >= [ASTRSP]

THEN:

            VARIATION IN STIRRUP SPACING IS NONE


THE ANSWER BELOW IS THE FINAL CONCLUSION.

1. FAIR POSSIBILITY OF FAILURE CAUSED BY ERROR IN CONCRETE STRENGTH
2. HIGH POSSIBILITY OF FAILURE CAUSED BY ERROR IN BEAM EFFECTIVE DEPTH
3. HIGH  POSSIBILITY  OF  FAILURE  CAUSED BY VERTICAL UNIFORM LIVE LOAD AND
   CONCENTRATED LOAD.
```

Figure 3. Cont'd

```
 1.  UNIFORM LIVE LOAD ON THE BEAM IS TRUE
 2.  CONCENTRATED LOAD ON THE BEAM IS TRUE
 3.  AMOUNT OF CRUSHING OF CONCRETE AT CENTER TOP IS  MEDIUM
 4.  AMOUNT OF AVERAGE CRACK SIZE AT ENDS IS MEDIUM
 5.  VARIABLE [CW] = 0.5
 6.  VARIABLE [CP] = 15
 7.  VARIABLE [DW] = 0.07
 8.  VARIABLE [CL] = 240
 9.  VARIABLE [AWIDTH] = 12
10.  VARIABLE [SWIDTH] = 12
11.  VARIABLE [ACONCST] = 3900
12.  VARIABLE [SCONCST] = 4000
13.  VARIABLE [AREBARST] = 60000
14.  VARIABLE [SREBARST] = 60000
15.  VARIABLE [AREBARDP] = 18
16.  VARIABLE [SREBARDP] = 20
17.  VARIABLE [AREBARAR] = 6
18.  VARIABLE [SREBARAR] = 6
19.  VARIABLE [ASTRSP] =   4
20.  VARIABLE [SSTRSP] =   4
21.  VARIABLE [PAMR] = 4846.75400
22.  VARIABLE [PSMR] = 5607.00000
23.  VARIABLE [PASR] = 46.77840
24.  VARIABLE [PSSR] = 52.35787


THE ANSWER BELOW IS THE FINAL CONCLUSION.

1. FAIR POSSIBILITY OF FAILURE CAUSED BY ERROR IN CONCRETE STRENGTH
2. HIGH POSSIBILITY OF FAILURE CAUSED BY ERROR IN BEAM EFFECTIVE DEPTH
3. HIGH  POSSIBILITY  OF  FAILURE  CAUSED BY VERTICAL UNIFORM LIVE LOAD AND
   CONCENTRATED LOAD.
```

Figure 4. A Direct Answer to the Conclusion of Example in Fig. 3

TABLE 1. VARIABLES USED IN FDES

VARIABLE	DESCRIPTION
ACONCST	ACTUAL CONCRETE STRENGTH (PSI)
AMR	ACTUAL MOMENT RESISTANCE (KIPS-IN)
AML	ACTUAL MOMENT LOAD (KIPS-IN)
AMCL	ACTUAL MOMENT DUE TO CONCENTRATED LOAD
AMULL	ACTUAL MOMENT DUE TO UNIFORM LIVE LOAD
AMUDL	ACTUAL MOMENT DUE TO UNIFORM DEAD LOAD
AREBARAR	ACTUAL REBAR AREA (IN SQ)
AREBARDP	ACTUAL BEAM EFFECTIVE DEPTH (IN)
AREBARST	ACTUAL REBAR STRENGTH (PSI)
ASL	ACTUAL SHEAR LOAD (KIPS)
ASR	ACTUAL SHEAR RESISTANCE (KIPS)
ASCL	ACTUAL SHEAR DUE TO CONCENTRATED LOAD
ASULL	ACTUAL SHEAR DUE TO UNIFORM LIVE LOAD
ASUDL	ACTUAL SHEAR DUE TO UNIFORM DEAD LOAD
ASTRP	ACTUAL STIRRUP SPACING (IN)
AWIDTH	ACTUAL BEAM WIDTH (IN)
CW	ACTUAL UNIFORM LIVE LOAD (KIPS/IN)
CL	ACTUAL BEAM SPAN (IN)
CP	CONCENTRATED LOAD (KIPS)
DW	ACTUAL UNIFORM DEAD LOAD (KIPS/IN)
PAMR	PROGRAM AMR
PASR	PROGRAM ASR
PSMR	PROGRAM SMR
PSSR	PROGRAM SSR
SCONCST	SPECIFIED CONCRETE STRENGTH (PSI)
SMR	SPECIFIED MOMENT RESISTANCE (KIPS-IN)
SREBARST	SPECIFIED REBAR STRENGTH (PSI)
SREBARDP	SPECIFIED BEAM EFFECTIVE DEPTH (IN)
SREBARAR	SPECIFIED REBAR AREA (IN SQ)
SSR	SPECIFIED SHEAR RESISTANCE (KIPS)
SSTRP	SPECIFIED STIRRUP SPACING (IN)
SWIDTH	SPECIFIED BEAM WIDTH (IN)