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# Fault Tree Model for Failure Path Prediction of Bolted Steel Tension Member in a Structural System

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**ABSTRACT:**
Fault tree is a graphical representation of various sequential combinations of events which leads to the failure of any system, such as a structural system. In this paper it is shown that a fault tree model is also applicable to a critical element of a complex structural system. This will help to identify the different failure mode of a particular structural element which might eventually triggered a progressive collapse of the whole structural system. Non-redundant tension member generally regarded as a Fracture Critical Member (FCM) in a complex structural system, especially in bridge, failure of which may lead to immediate collapse of the structure. Limit state design is governed by the failure behavior of a structural element at its ultimate state. Globally, condition assessment of an existing structural system, particularly for bridges, Fracture Critical Inspection becomes very effective and mandatory in some countries. Fault tree model of tension member, presented in this paper can be conveniently used to identify the flaws in FCM if any, in an existing structural system and also as a check list for new design of tension member.
**KEYWORDS:** *Fault Tree, Tension Member, Fracture Critical, Limit State, Reliability, Boolean.*

## I. INTRODUCTION

Modern design philosophy recognizes that there is a finite chance of failure of a structure, however small it may be depending upon the individual reliability requirement of a particular structure.[6] A fracture critical members (FCM) is defined by "a steel member in tension, or with a tension element, whose failure would probably cause a portion of or the entire bridge to collapse." [7] While designing a real structure, primary aim of a structural engineer is to avoid a catastrophic failure of the structure. Limit State Design generally accepts the inelastic state of a steel structure but avoids any early or disproportionate failure of structural system when its response limit tends towards its ultimate state. Rupture of tension member, for example, bottom chord or diagonal member of a steel open web lattice girder bridge may lead to a disproportionate collapse without giving any prior warning.

**Fig.1: Typical Example of Fracture Critical Member**

In modern design all effort shall be made to avoid sudden failure of a structure by predicting the probable critical failure path that may occur during its life time. While designing a structure all attention shall be made to avoid any catastrophic collapse even in extreme consequences. In modern concept, design of tension member requires more rigorous check than erstwhile traditional design approach. It is immensely important for a practicing structural engineer to recognize the failure behaviors of a structural element for implementation of codified (e.g.IS-800:2007) guideline to the real world structural design. This paper reviewed the detail provision of tension member design guideline given in IS-800:2007 with essential input from other international codes and this has been done by identifying the probable failure mode through a probabilistic tool "Fault Tree Analysis".

## II. FAULT TREE

Fault Tree is based on a deductive top down approach, starting by considering a failure of structural member or system and the aims to deduct sequential events which could lead to the ultimate failure as a top event. [1]
A Fault Tree is a Boolean logic diagram comprised primarily of complex entity called "gates". In accordance with the rules of probability theorem,

AND gate which can be written in set algebraic form as

$P_f = P(A) \cap P(B) \cap P(C) \ldots$

In Boolean logic form it can be written as probability of failure, $P_f = P(A).\ P(B).\ P(C) \ldots$

So, $P_f = \prod_{i=1}^{n} P_{fi}$

and for OR gate as –

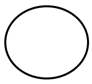
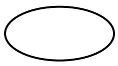
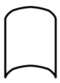
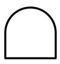
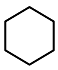
$P_f = P(A) \cup P(B) \cup P(C) \ldots$

In Boolean Logic form it can be written as Pf = P (A) + P (B) + P(C) +…

So, $P_f = 1 - \prod_{i=1}^{n} (1 - P_{fi})$

This Fault Tree includes the symbolic notations given in Table-1.

Table - 1

| Symbol | Name | Description |
|---|---|---|
|  | Basic Event | A basic initiating fault requiring no further development. |
|  | Intermediate Event | A fault event that occurs because of one or more antecedent causes acting through logic gates. |
|  | Conditioning Event | Specific conditions or restrictions that apply to any logic gates. |
|  | OR Gate | Output fault occurs if at least one of the input faults occurs. |
|  | AND Gate | Output faults occur if all of the input faults occur. |
|  | Inhibit Gate | Output faults occurs if the (single) input faults occurs in the presence of an enabling condition (the enabling condition is represented by a conditioning Event drawn to the right of the gate). |

## III. LIMIT STATE EQUATIONS for COLLAPSE of BOLTED TENSION MEMBER

### 3.1 Identification of random variables governs the Limit State design of tension member

Where

$\gamma_i$ = Partial Safety Factor for i=DL, LL, WL, EL…..

Ti = Total Design tension for i=DL, LL, WL, EL…..

$A_g$ = Gross sectional area of member / gusset.

$A_n$ = Net sectional area of member.

$A_{nc}$= Net sectional area of the connected part.

$A_{go}$ = Gross sectional area of outstand part or unconnected portion.

$A_{vg}$ = Minimum gross area in shear along bolt line parallel to external force.

$A_{vn}$ = Minimum net area in shear along bolt line parallel to external force.

$A_{tg}$ = Minimum gross area in tension from the bolt hole to the toe of the angle, end bolt line, perpendicular to the line of force.

$A_{tn}$ = Minimum net area in tension from the bolt hole to the toe of the angle, end bolt line, perpendicular to the line of force.

$A_{sb}$ = Nominal plain shank area of the bolt

$A_{nb}$ = net shank area of the bolt at threads, may be taken as the area corresponding to root diameter at the thread.

β= Shear lag co-efficient.

$b_s$= shear lag width .

t=summation of the thicknesses of the connected plates experiencing bearing stress in the same direction, or if the bolts are countersunk, the thickness of the plate minus one half of the depth of countersinking (for bolted connection)

g= gauge distance between the bolt holes

n = number of bolts

$n_n$ = number of shear planes with threads intercepting the shear plane

$n_s$ = number of shear planes without threads intercepting the shear plane

$f_y$= yield stress in N/mm2

$f_{yb}$= yield stress of bolt in N/mm2

$f_u$= ultimate stress of the material in N/mm2

$f_{ub}$= ultimate tensile stress of bolt in N/mm2

$\gamma_{m0}$= partial safety factor for failure in tension by yielding

$\gamma_{m1}$= partial safety factor for failure at ultimate stress

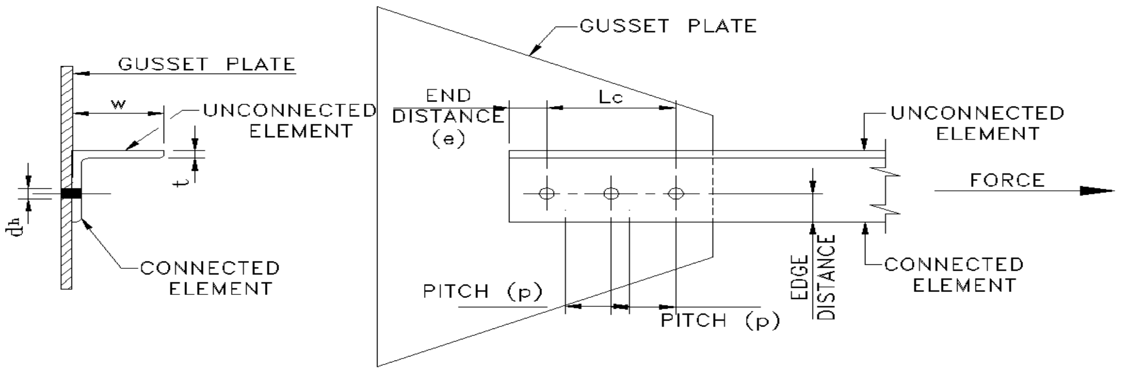



**Fig.2: A Typical Connection Detail of Bolted Tension Member**

i) Limit State of yielding of member / gusset plate

$(\sum\gamma_i T_i - A_g.\ f_y / \gamma_{m0}) <= 0$

ii) Limit State of Rupture of net section member/ gusset plate

a) $(\sum\gamma_i T_i - 0.9.\ A_n.\ f_u/\gamma_{m1}) <= 0$

b) $(\sum\gamma_i T_i - 0.9.\ A_{nc}.\ f_u/\gamma_{m1} + \beta.\ A_{go}.\ f_y/\gamma_{m0}) <= 0$

iii) Limit State of block shear of member/ gusset plate

a) $(\sum\gamma_i T_i - (A_{vg}.\ f_y/\surd 3.\gamma_{m0} + 0.9.\ A_{tn}.\ f_u/\gamma_{m1})) <= 0$

b) $(\sum\gamma_i T_i - (0.9 \text{ x } A_{nc}.\ f_u/\gamma_{m1} + \beta \text{ x } A_{go} \text{ x } f_y/\gamma_{m0}))<= 0$

iv) Limit State of Shear failure of Bolted connection-

$(\sum\gamma_i T_i - ((f_u/\surd 3).(n_n\ .A_{nb} + n_s\ .A_{sb}\ ) /\gamma_{mb})) <= 0$

v) Limit State of Bearing failure of Bolted connection -

$(\sum\gamma_i T_i - 2.5\ .\ k_b\ .\ d\ .\ t\ .\ f_u / \gamma_{mb}) <= 0$

where $k_b$ = smaller of $[(e/3.d_0),((\ p/3.d_0) - 0.25),(f_{ub}/f_u),1]$

vi) Limit State of Tension failure of Bolted connection -

$(\sum\gamma_i T_i - 0.9\ .\ f_{ub}\ .\ A_n / \gamma_{mb}) <= 0$

**3.2 Fault Tree Model of Tension Member:**

Fault Tree model of bolted tension member is simulated considering the three main connection element – Member, Gusset, Bolted connections.

**Fault Tree Model:**

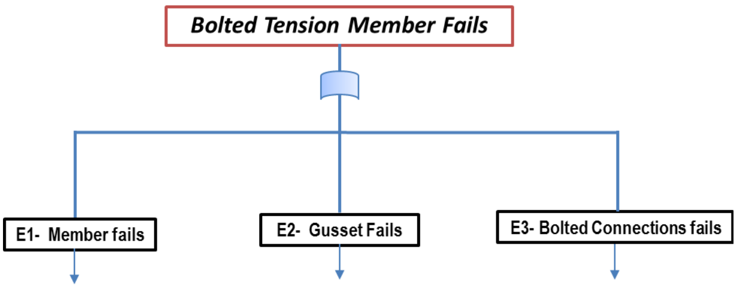



**Fig.3.1 FT of Tension Member & Connection Failure – Top Events**

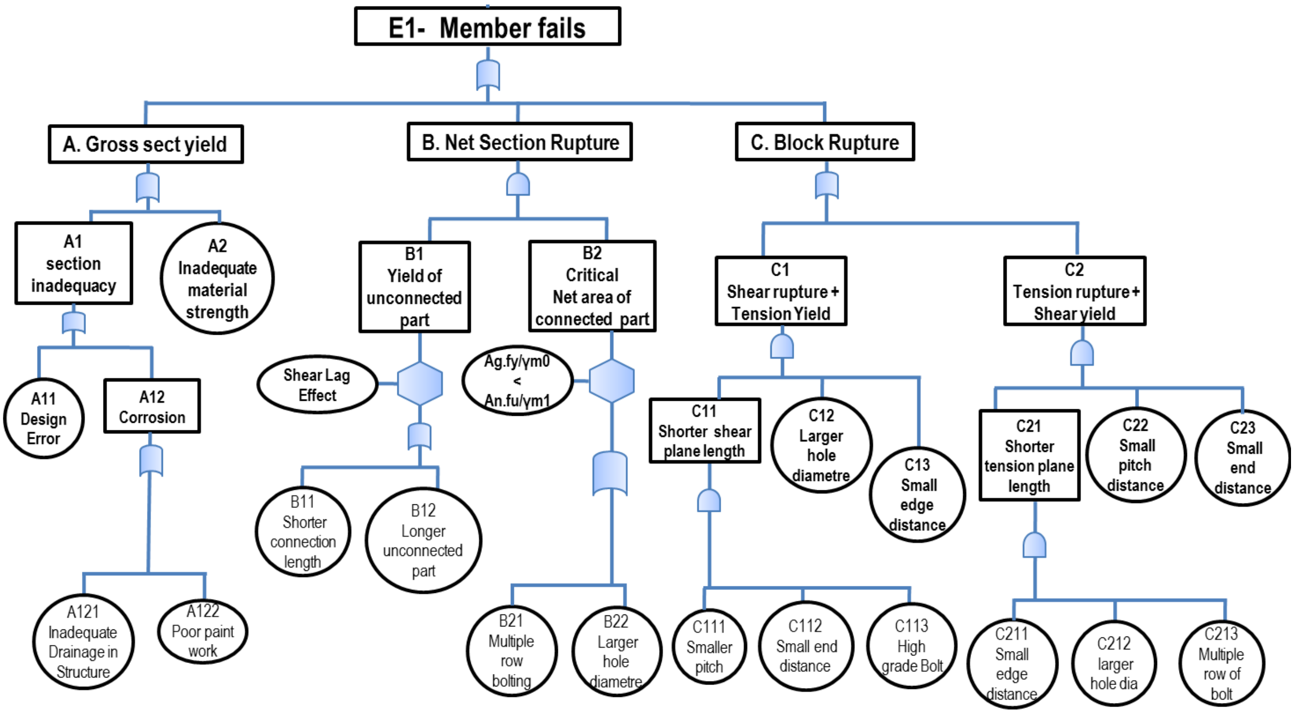



**Fig.3.2 FT of Tension Member for Collapse of Member elements**

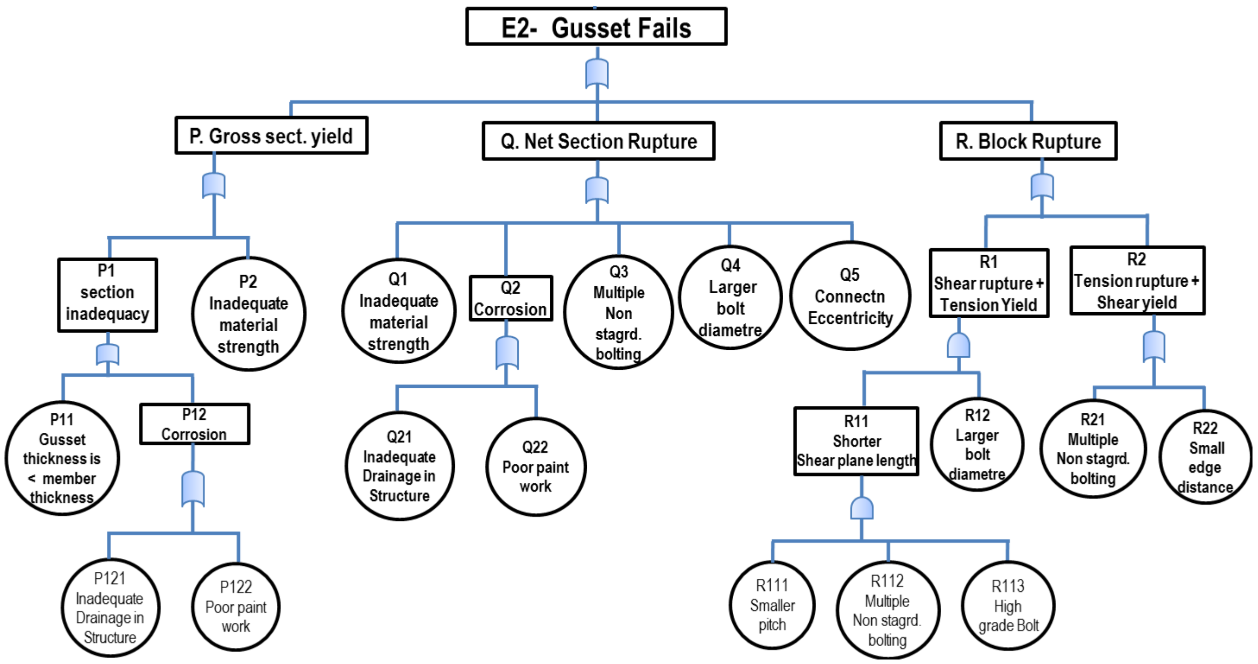



**Fig.3.3 FT of Tension Member for Collapse of Gusset elements**

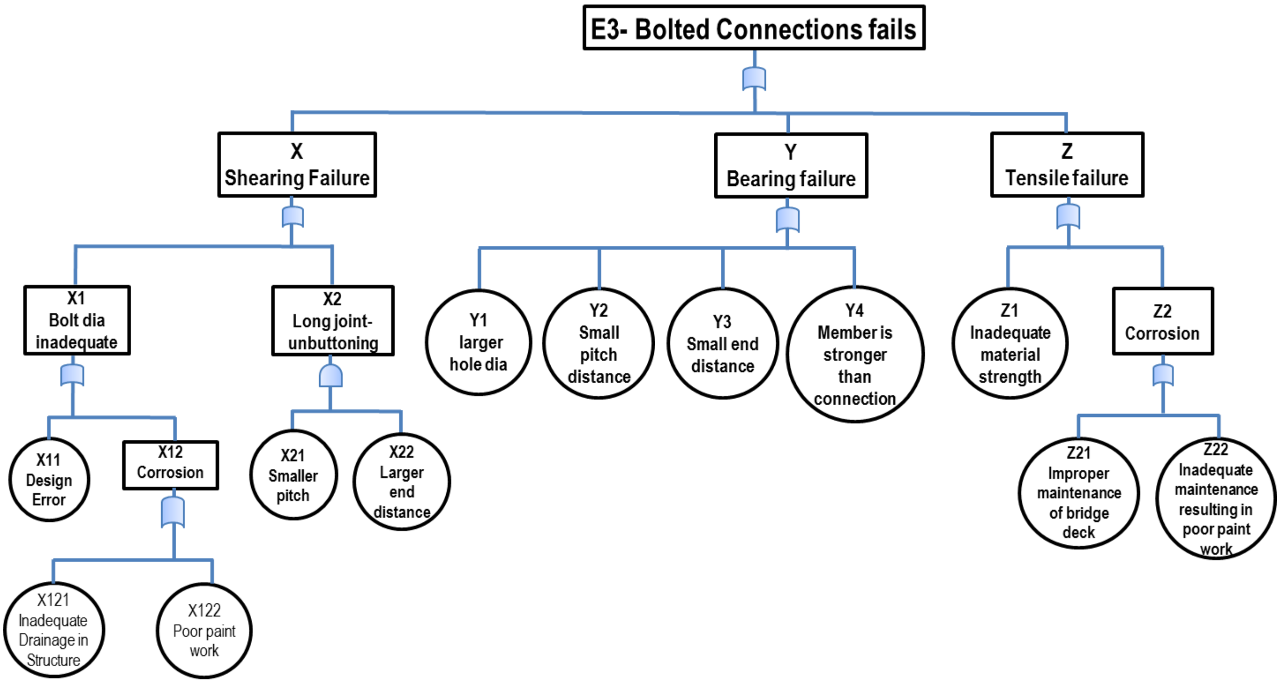



**Fig.3.4 FT of Tension Member for Collapse of Bolted Connections**

### 3.3 Event Description for the above Fault Tree

E1–Failure of tension member due to the main member failure

E2–Failure of tension member due to the gusset member failure

E3–Failure of tension member due to bolted connection failure

A – Main member fails due to gross section yielding

B - Main member fails due to net section rupture

C - Main member fails due to block rupture of whole section

A1 – Gross section yields due to inadequate section size and strength

A2 – Gross section yields due to improper quality of material

A11 – Section is inadequate due to design error

A12 – Section became inadequate due to corrosion

A121 – Corrosion is due to improper maintenance of bridge deck

A122-Corrosion is due to poor quality of maintenance resulting in poor paint work

B1–Net cross section ruptures due to yielding of unconnected part

B2-Net cross section ruptures due to critical connected part

B11–Unconnected part yields due to shorter connection length ($L_c$) along with shear lag effect

B12-Unconnected part yields due to longer unconnected part along with the shear lag effect

B21–Net area of connected part fails due to connection eccentricity provided $A_g.f_y/g_{m0} < A_n.f_u/g_{m1}$.

B22 - Net area of connected part fails due to multiple row of bolting arrangement provided $A_g.f_y/g_{m0} < A_n.f_u/g_{m1}$.

B23 - Net area of connected part fails due to larger diameter of bolt hole provided $A_g.f_y/g_{m0} < A_n.f_u/g_{m1}$.

C1 –Block shear failure due to rupture in shear plane and yield in tension plane.

C2 –Block shear failure due to rupture in tension plane and yield in shear plane.

C11 – Rupture of shear plane due to shorter shear plane length.

C12 – Yielding of tension plane occurs due to larger bolt hole diameter.*

C13 – Yielding of tension plane occurs due to small edge distance ****

C111 – Shorter Shear plane fails due to smaller pitch distance**

C112 - Shorter Shear plane fails due to smaller end distance***

C113 - Shorter Shear plane fails due to higher grade of bolt

C21 – Rupture of tension plane occurs due to shorter tension plane length.

C22 – Yield of shear plane occurs due to smaller pitch distance.**

C23 – Yield of shear plane occurs due to smaller end distance.***

C211 – Rupture of tension plane occurs due to smaller edge distance****
C213 - Rupture of tension plane occurs due to multiple row of bolting arrangement.*****
P1 - Gross section of gusset yields due to inadequate section size and strength
P2 – Gross section of gusset yields due to improper quality of material
P11 – Thickness of gusset is less than member thickness
P12 – Gusset Section became inadequate due to corrosion
P121 – Corrosion is due to improper maintenance of bridge deck
P122 - Corrosion is due to poor quality of maintenance resulting in poor paint work
Q1 – Gross section of gusset yields due to improper quality of material
Q2 – Net section of gusset yields due to corrosion
Q21 – Corrosion is due to improper maintenance of bridge deck
Q22 - Corrosion is due to poor quality of maintenance resulting in poor paint work
Q3 – Rupture of net area occurs due to multiple row of bolting arrangement
Q4 - Rupture of net area occurs due to larger diameter of bolt hole in gusset.
Q5 - Net area of gusset fails due to connection eccentricity
R1 –Block shear failure of gusset due to rupture in shear plane and yield in tension plane.
R2 –Block shear failure of gusset due to rupture in tension plane and yield in shear plane.
R11 – Rupture of shear plane in gusset due to shorter shear plane length.
R12 - Yielding of tension plane occurs due to larger bolt hole diameter.
R111 - Shear plane of gusset fails due to smaller pitch distance
R112 - Shear plane of gusset fails due multiple row of bolting arrangement
R113 - Shear plane of gusset fails due higher grade of bolt
R21 – Rupture and yield of tension and shear plane respectively for multiple row bolting arrangement in gusset.
R22 - Rupture and yield of tension and shear plane respectively for smaller edge distance
X – Connection fails due to shear failure of bolts
Y – Connection fails due to bearing failure of bolts
Z – Connection fails due to tension failure of bolts.
X1 – Shear failure of bolts occurs due to inadequate bolt diameter
X11 – Bolt diameter is inadequate due to design inaccuracy
X12 – Bolts became inadequate due to corrosion
X121 – Corrosion is due to improper maintenance of bridge deck
X122 - Corrosion is due to poor quality of maintenance resulting in poor paint work
X2 – Shearing of bolt occurs due to the unbuttoning effect in long joints i.e. End bolts reach the ultimate stress faster i.e. fails faster than intermediate bolts
Y1 – Bearing failure of bolts occur due to larger diameter of bolt hole
Y2 – Bearing failure of bolts occur due to smaller pitch distance**
Y3 – Bearing failure of bolts occur due to smaller end distance****
Y4 – Bearing failure of bolts occur due to higher strength of member than connection
Z1 –Tensile failure of bolts occur due to improper quality of material of bolt
Z2 - Bolts became inadequate due to corrosion and fails in tension
Z21 – Corrosion is due to improper maintenance of bridge deck
Z22- Corrosion is due to poor quality of maintenance resulting in poor paint work

* Size of Bolt Hole = Nominal diameter of Bolt + Clearance
Clearance should be maximum 3mm minimum 1mm generally for 16-22 mm diameter bolts 2 mm is taken less than that diameter 1mm should be taken and for greater than 24mm diameter bolt 3mm is taken.
** Pitch distance = Centre to centre distance between fastener
It should not be less than 2.5 times of the nominal diameter of bolt or fastener.
For tension member it should not exceed 16t or 200 mm where t is the thickness of thinner plate
In no case pitch distance should exceed 32t or 300 mm.
*** End distance = distance in the direction of stress from the centre of hole to the end of the element.
It should not be less than 1.7 times of hole diameter in case of sheared or hand flame cut edge
And 1.5 times of the hole diameter in case of rolled, machine-flame cut, sawn and plane edges.
**** Edge distance = distance at right angles to the direction of stress from the centre of hole to the adjacent edge.
It should not be less than 1.7 times of hole diameter in case of sheared or hand flame cut edge
And 1.5 times of the hole diameter in case of rolled, machine-flame cut, sawn and plane edges.
***** Gauge distance – it should not exceed 75mm for staggered and multiple row of bolting arrangement.

### 3.4 Boolean Operation

Boolean algebra is particularly important when the situations involving dichotomy.[1] A Fault tree can be translated to equivalent set of Boolean equation

and solving them to get a minimal cut set. A minimal cut set is a smallest combination of component failures which, if they all occur, will cause the top event to occur. [1] By Boolean operation on the fault tree the following minimal cut set is obtained.
**A11U A12 UA122 U A2 U B21 U B22 U B23 U C13 U C23 U (C22 ∩ Z2) U Y4 U P11**
And the corresponding FT model is shown in Fig.4.

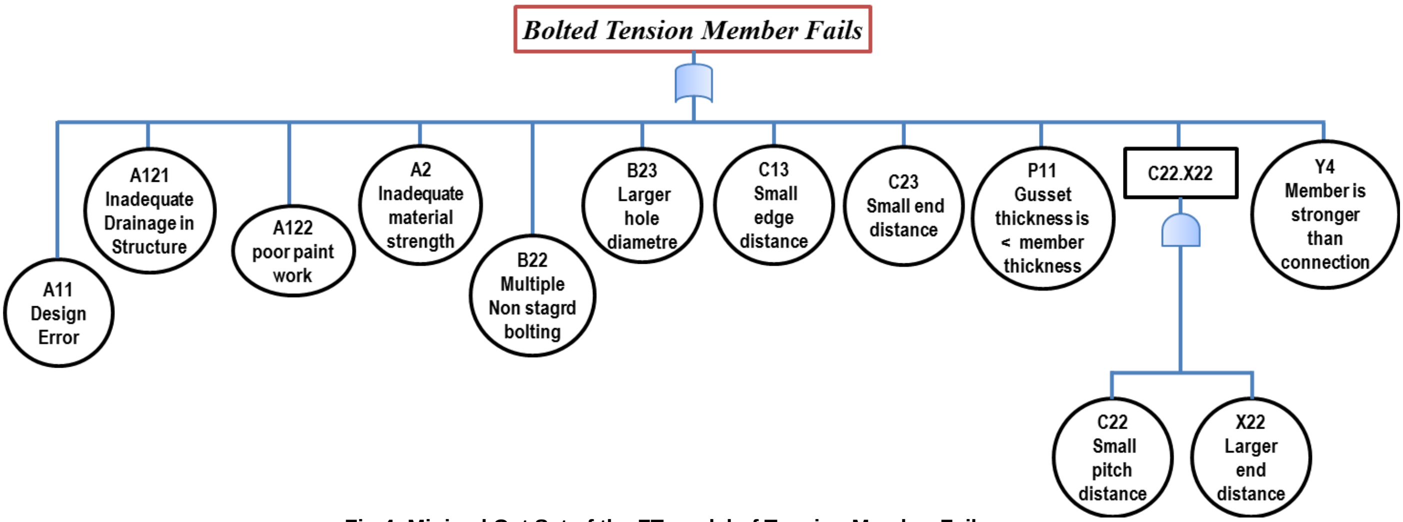



**Fig.4: Minimal Cut Set of the FT model of Tension Member Failure**

### 3.5 Findings

3.5.1 Minimal Cut Set as arrived by Boolean operation on the Fault Tree model indicates that there are some defined critical failure paths for a bolted tension member.
3.5.2 In Fracture Critical Bridge inspection this minimal cut set can easily and directly be applied for detecting the qualitative probable failure path.
3.5.3 This Fault Tree model can also efficiently applied as a checklist in design of a new structural system where the tension member is always a fracture critical member.
3.5.4 This approach can also be used for other member category like compression member, flexural member or member under biaxial stresses to prepare efficient checklist for inspection of existing structure and design of new structure.

## IV. SUMMARY & CONCLUSION

4.1 It is observed that Fault tree model can also be applied to the design and appraisal of a typical member with multiple numbers of probable failure paths as it is generally applied for a complex structural system.
4.2 Separate FT model is required for FCM component which includes the tension flange of cross beam and stringer in a steel bridge structure which is not included in this present study.
4.3 Qualitative Inspection of an existing truss or lattice girder is a first step in condition assessment work. Tension member and tension component as identified in FCM inspection shall require to be further checked individually to ascertain the flaws in the member or its connection if any.
4.4 The Fault tree model and its minimal cut set obtained after Boolean operation for a typical tension member can be used directly as a checklist to evaluate the existing status and risk of failure of the bridge or structure.
4.5 A graphical representation of failure path can ensure flawless Design, detailing and fabrication of non-redundant tension member and tension components are becoming more important because of its fracture critical character in complex structural system to avoid any fracture failure leading to catastrophic collapse of the system.
4.6 This FTA is a qualitative analysis as presented here for general checklist purpose for appraisal of an existing or new design of tension member. This FTA model can be further extended for its quantitative evaluation of a particular case of failure by direct input of statistical data if available (for this type of failure) in the minimal cut set to ascertain the most probable cause of the particular failure event.

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