Investigating Bridge Deck Deterioration using Failure Analysis Technique and Markov Chains

by

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Project and Report submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Civil Engineering

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May, 1990

Blacksburg, Virginia

Acknowledgements

The author wishes to express his appreciation and thanks to the following individuals for their aid and encouragement during the completion of this study.

Dr. Drew, Coordinator, Transportation Program and Chairman of the committee; for the initial impetus in topic selection, council and advice at all stages of the study.

Dr. Walker and Dr. Trani for their assistance, constructive criticism and advice throughout this study and during the author's pursuit for the Master of Science degree in Civil Engineering.

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ABBREVIATIONS AND NOTATIONS

BMS	Bridge Management System
C/I	Condition Index
FHWA	Federal Highway Administration, Washington D.C.
FMEA	Failure Mode, Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FTA	Fault Tree Analysis
NCHRP	National Cooperative Highway Research Program
NBI	National Bridge Inventory
OECD	Organization for Economic Co-operation & Development, Paris.
SIF	Safety Index Factor
TRB	Transportation Research Board
USDOT	United States Department of Transportation

1.0 INTRODUCTION

1.1 Background - Bridges

Bridges are the key elements in a road network. They are the links across physical obstructions and man made structures, and are designed to provide safe and quick passage to vehicles and pedestrians alike, with the least inconvenience. Bridges in a road network are important because of their purpose, location, complex design, investment, aesthetics and for the unfavorable consequences created when they fail to perform the desired function due to impaired capacity

Bridges can be classified into different categories based on material used for construction, type of structure, number of spans, and location as shown in Table 1, page 3.

The 1900s saw the use of concrete, reinforced concrete and steel as the most favored materials for bridge construction replacing the traditionally used wood and stone because of availability, durability, cost, flexibility in design and construction, longer service life and due to the inherent strength of these materials which allowed the construction of multi-lane, multi-spanned structures to accommodate heavier axle loads and higher traffic volumes of many different types of vehicles.

The 1900s, especially the 1960s, saw the emergence of prestressed concrete technology which was adapted into bridge engineering and construction quickly. Changes in design practices aimed at cutting construction costs and material costs gave way to components which were slender and thinner in cross-sectional area but, without compromising on structural stability, service life or aesthetics.

Table 1. Bridge Types and Numbers, (NBI Statistics)

BRIDGE TYPES	NUMBERS	
CONCRETE SLAB	42,450	
CONCRETE TEE	26,798	
CONTINUOUS CONCRETE SLAB	21,958	
CONCRETE STRINGER	16,884	
CONTINUOUS CONCRETE TEE	7,467	SUBTOTAL : 115,557
CONCRETE DECK ARCH	6,245	
PRESTRESSED CONCRETE SLAB	5,561	
PRESTRESSED CONCRETE TEE	4,687	
PRESTRESSED CONCRETE STRINGER	26,654	
PRESTRESSED CONCRETE MULTIPLE BOX	16,727	
STEEL STRINGER	130,892	
CONTINUOUS STEEL STRINGER	36,488	
STEEL THROUGH TRUSS	9224	
STEEL GIRDER FLOOR BEAM	31,206	
TIMBER STRINGER	58,012	
TUNNEL AND CULVERTS	132,747	
TOTAL	574,000	

Nowhere in the world is the roadway network as extensive as in the United States. About half the bridges in the OECD countries of Europe and North America belong to the U.S. [9]. There are approximately 575,000 bridges in the States including drains and culverts [4], and about 40 percent of them are classified as either structurally or functionally deficient by FHWA. A bridge is structurally deficient when the structure or a part or component is not able to support the design load for which they are intended and functionally deficient when the geometrical and or locational requirements do not suit the traffic demand at the present and any deficiency for that matter require repair, rehabilitation, strengthening or replacement, based on the magnitude of the deficiency, to restore the bridge component or subsystem to the desired level of performance, keeping in mind the safety and time value of the users of the facility.

1.2 Significance of the Problem

About half of all the bridges in the U.S. were constructed before the 1940s while the rest were constructed until the 1980s. Increase in traffic volumes, higher axle loads from freight vehicles, corrosion of reinforcement; expedited by the use of deicing salts, inadequate design, poor quality materials, inadequate or bad construction practices, unsystematic maintenance and repair procedures and weathering, not to mention the different construction and maintenance policies followed by the various state and county agencies have all contributed to structural and functional deficiency of bridges in the United States. Catastrophic failures, such as earthquake induced or due to floods, foundation movement and differential settlement are considered rare and are negligible throughout the OECD countries [14]. However, deterioration in the form of spalling, cracking, scaling, popouts and leaching of concrete, and corrosion of steel which occur continuously over a long period of time; beginning with the first day of construction, is a serious problem requiring immediate attention and billions of dollars in maintenance and repair funds [4][13].

1.3 Problem Definition

Deterioration in concrete and reinforced concrete bridges - the topic of this study; is as rampant and extensive as in the rest of the bridge types. Concrete and reinforced concrete bridges have different categories as shown Table 1, page 3 But, the problems of deterioration remain the same in all the categories. Figures 1 to 4 [24], show some of the statistics condensed from the NBI, maintained by the Bridge Division of the FHWA. Table 1 and Figure 3, page 8 indicate that approximately 20 percent of all the bridges have reinforced concrete decks and about 28,000 of these require some sort of structural work to maintain them in serviceable condition. Going by the Safety Index Factor, Figure 1, page 9, which is determined from Superstructure Condition Rating, Substructure Condition Rating and the Inventory Rating, which in turn are determined following the guidelines stipulated by the "Recording and Coding Guide for the Nations Bridges ", show an average of 41 Safety Index Points out of the possible 50. This information clearly indicates that the concrete bridges have no structural inadequacy problem caused by catastrophic failures, and the loss in 9 Safety Index Points is attributed to deterioration, especially deck deterioration. Bridges are estimated to have a serviceable life of around 70 years and Figure 2, page 7 indicates that on an average, concrete bridges have well past half their service life. Should the factors which influence deterioration such as, increase in traffic volume, corrosion, higher axle loads from freight vehicles, and weathering tend to continue then the bridges are bound to deteriorate more rapidly than expected, requiring costly repair works to attain the estimated service life.

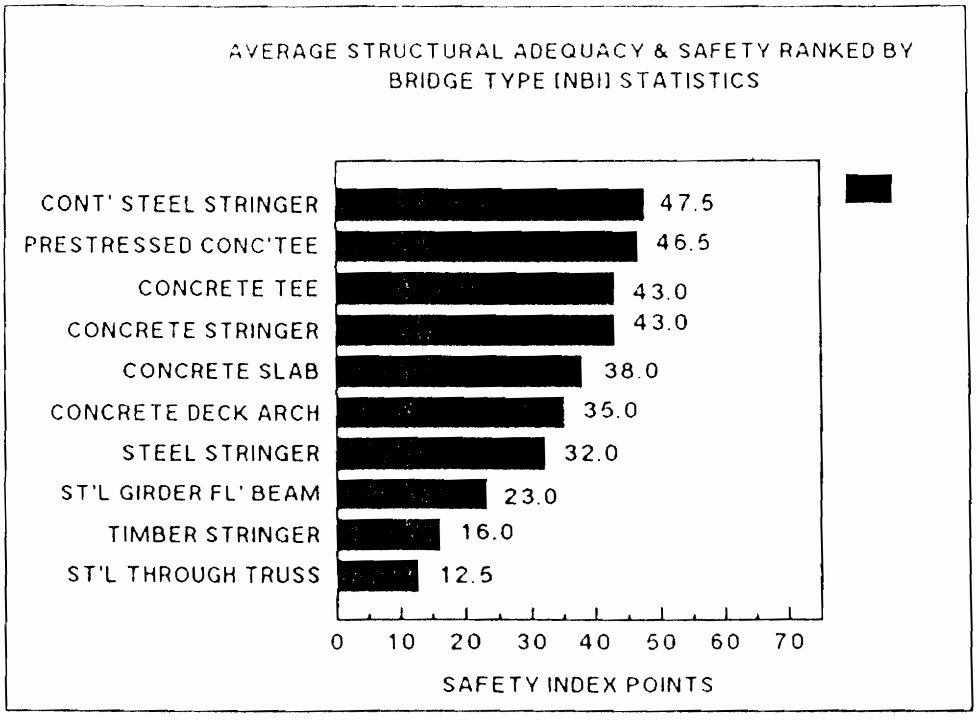


Figure 1. Structural Adequacy and Safety by Bridge Type.: The average of SIPs for Concrete Tee, Concrete Slab and Concrete Stringer is 41.

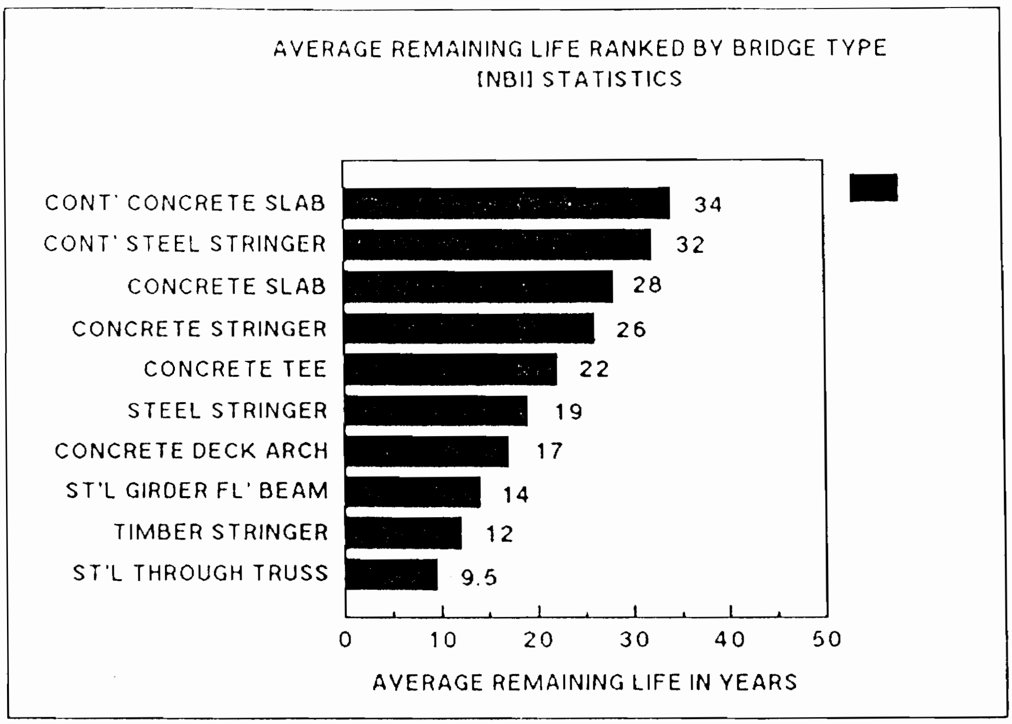


Figure 2. Average Remaining Life Ranked by Bridge Type.: Average for Concrete Tee, Slab, Stringer and Continuous Concrete Slab is 27.5 years.

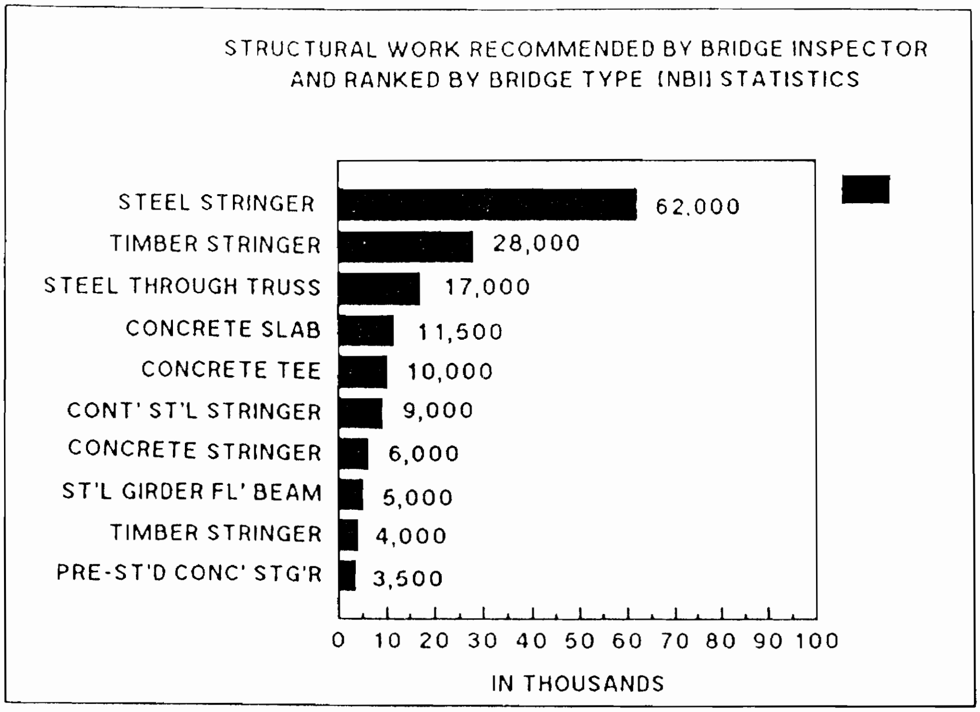


Figure 3. Structural Work Recommended to Bridges by Bridge Type.: Bridges with concrete decks requiring structural work is around 27,500.

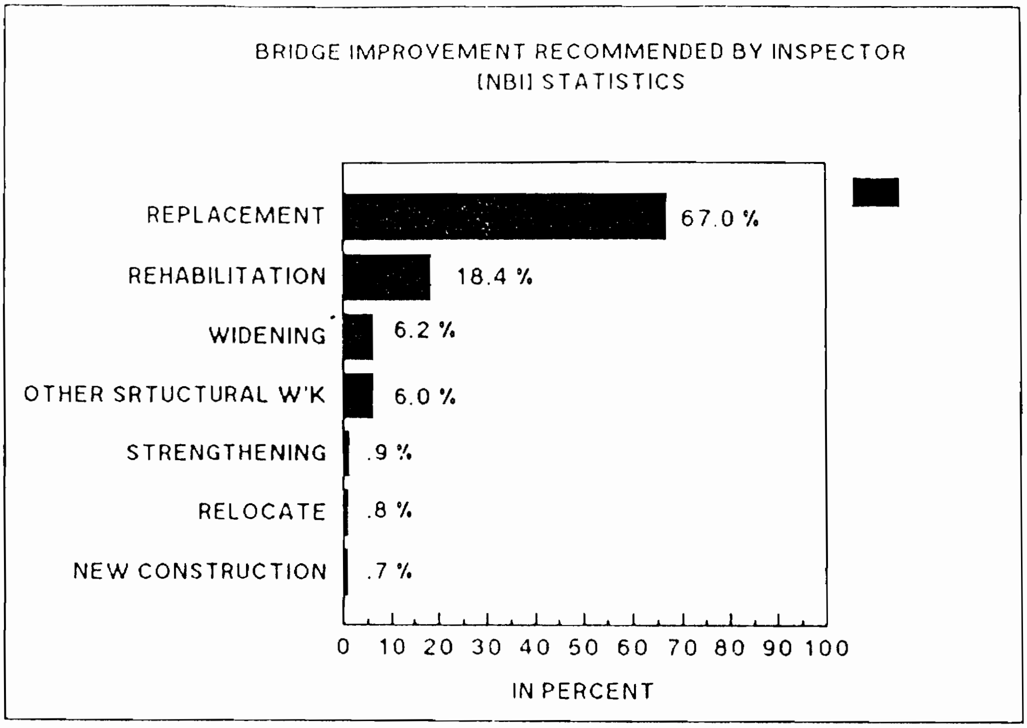


Figure 4. Bridge Improvements Recommended for all Bridges in the U.S.: Replacement is unduly high compared to Rehabilitation.

Concrete is a material which is good in compression but weak in tension. Concrete gradually disintegrates on exposure to weathering. A component which is horizontal, like the bridge deck, supporting traffic loads which induce shear forces and subject to bending moments accompanied by direct exposure to weathering agents such as; temperature variation, rain, snow, frost, freeze and thaw, fumes from the vehicles, traffic impact and braking, all contribute in making the deck the prime candidate for deterioration. No other component in the bridge has deteriorated as badly as the deck and its subcomponents such as the joints and overlays. The floor system supporting the deck, which is made up of longitudinal and traverse beams, bearings and the vertical members such as the columns, bents, footings and piles are in pretty good condition because they do not directly support the live loads from traffic and are not as exposed as the deck to weathering.

There are many quantitative and qualitative techniques making use of the recorded bridge deterioration, maintenance and rehabilitation information to investigate deterioration. Many mathematical and statistical models have been developed to identify and quantify bridge deterioration. Some researchers, especially, in the areas of Pavement Management [23] and Structural Analysis of Multi Storied Buildings and Parking Lots [3] have made an effort to apply systems engineering concepts such as Decision Tables, Decision Trees and Failure Analysis Techniques to investigate their respective problem areas. But systems engineering techniques have found little application to make a thorough investigation of bridge deterioration, especially the bridge deck deterioration. This study is an attempt in investigating bridge deck deterioration and failure analysis techniques such as, Failure Mode Effects Analysis [FMEA], Fault Tree Analysis [FTA] and Decision Trees are applied to investigate bridge deck deterioration to deduce the basic events which lead to failure due to deterioration alone and to find the failure probability range at any given time during the service life of an newly constructed or already existing bridge deck.

1.4 Organization

In this study the bridge is visualized as a system. The smallest parts in the bridge system are the subcomponents. Subcomponents form a component and many components form a subsystem. And subsystems form the bridge system. Figure 5, page 12 identifies all the above levels and the important components in each level. This arrangement closely resembles the structural arrangement of the bridge components, carrying and transferring live and dead loads from one level to the next lower level. However, some of the components identified in the figure, like the drains and utilities are not load carrying components.

The next logical step would be to define the function of each component in the subsystem and its relationship to those components existing immediatly above and below it. The third step is to investigate; if the component, which is important to the structural stability of the bridge, is affected by deterioration; and if true, to find the basic events causing deterioration. Once this is complete, then the questions: *Does component failure occur.* and *will component failure affect the upper and lower subsystems and finally the bridge system,* has to be answered. But, in a bridge system even though the function of each component is well understood, the interrelationship between them as far as the effect of deterioration of one on the other is not clear.

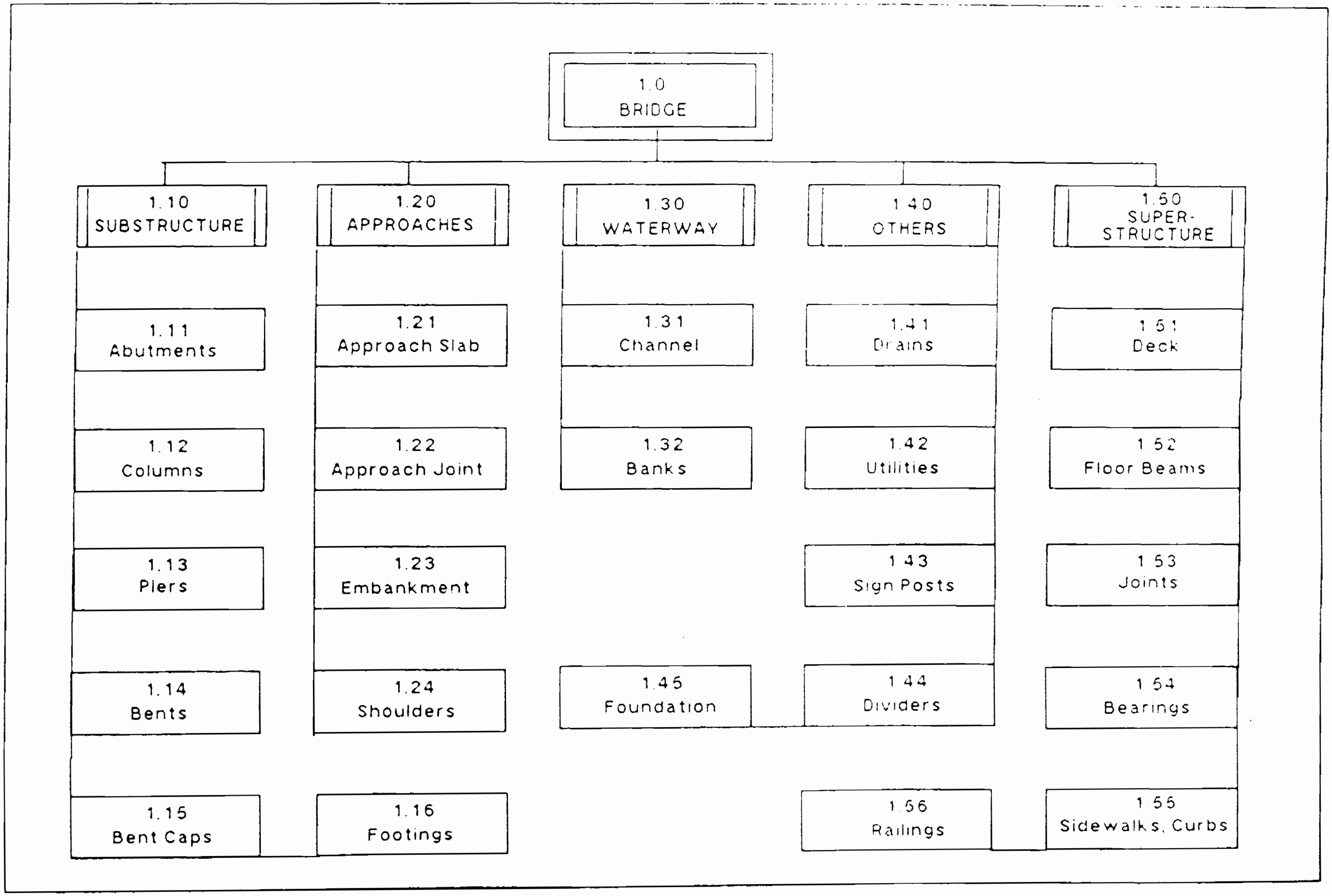


Figure 5. Bridge System, Subsystems and Components.: The numbering identifies the levels and the items under each level.

Even the Structural Inventory and Appraisal form, which is the standard form used by bridge inspectors of most of the states to evaluate the condition of the bridge, identify deck as the only component worth considering for a separate evaluation, while the rest of the components such as bearings, floor beams and columns etc., are identified and evaluated at the subsystem level, like in the Superstructure [item 59], the Substructure [item 60], [12][25]. This itemization is done out of careful evaluation of the bridges from years of field investigation and data analysis. In this study every step is taken to keep the itemization in the same way as in reference 21, and a thorough investigation of deck deterioration is undertaken because, deck deterioration has precedence over any other component deterioration and the causes and factors causing deck deterioration remain the same as for any other component or subsystem. The way this is done is by doing Failure Analysis. Failure Analysis identifies the causes and the basic events causing the various forms of deterioration. The extent, severity, significance and the critical locations of the defects causing deterioration, such as corrosion, spalling, scaling etc., in the identified components are investigated and recorded by doing Failure Analysis. Decision Tree is used to work on the information provided by Failure Analysis to quantify the effect of each combination of extent, severity and significance and to assign a numerical value to each combination which is then related to the Condition Index. Condition Indices, Figure 8, page 29, is a range of numerical values from 9 to 0, used to rate the condition of the deck, the superstructure and the substructure by bridge engineers in accordance with the guidelines stipulated in the "Recording and Coding Guide for the Nations Bridges." A plot of Condition Index versus Service Life for the bridge deck, is developed separately by using Markov Chains [2][22][23] and the magnitude of deterioration indicated by the condition index is then referred against the age of the component to find the approximate time when deterioration failure occur and to find the associated range of reliability.

2.0 LITERATURE REVIEW

2.1 Bridge Management System

Recognizing that a Bridge Management System was a high priority of many states [13], NCHRP allocated funds for the research and development of a model BMS. The specific objective of NCHRP project 12-28(2) was to develop a form of effective network level bridge management that included the following;

- Engineering methods to assess present and future needs of existing bridges.
- Guidelines to determine cost effective alternatives both with and without financial constraints.
- Priority treatment of needs through the use of generalized work activities.
- Flexibility to accommodate a variety of policy approaches.
- Flexibility to accommodate future expansion to the project level.

Essential BMS Modules:

1. Data Base Module
2. Network Level MR&R Selection Module

3. Maintenance Module
4. Historical Data Analysis Module
5. Project Level Interface Module
6. Reporting Module.

The Data Base Module is the core of the system and all the other submodules use and operate on the data to perform the functions of bridge management.

The data base in the module can be classified into different categories such as:

- Bridge Inventory Data
- Bridge Condition Data
- Bridge Maintenance and Repair Data

Bridge condition data include information produced during bridge inspections and appraisals. This data is used in choosing and prioritizing the appropriate bridge MR&R selections. Condition ratings available in the National Bridge Standards exist only in the form of a single severity rating for each of the several major components of the bridge. The Model BMS should contain data which are based on the severity and extent of specific distresses. Each of the bridge components contain elements to be rated individually. The rating consists of highly detailed information rather than merely the severity of some general condition as in the current practice. The actual distresses present for each element and the severity and extent of these distresses allow understanding of the problems on each bridge and the prediction of specific selections for MR&R strategies.

2.2 Concrete Deterioration

Many bridges across the country [4][5][6][7][8][13][18], including, the recently built ones show some degree of deterioration. Deterioration is defined as any significant change in the physical, chemical, or mechanical property of a structure or of any of its components. Reinforced concrete which is the most widely used material is a low cost, durable, multi-use building material. But the effects of inadequate design, poor quality mix, unsatisfactory construction and maintenance has resulted in the relatively rapid deterioration of reinforced concrete structures. Some of the defects which are indicators to deterioration in reinforced concrete are cracking, scaling, spalling, delaminations, leaching, deformations stains, ride quality, patching and other repairs. Some factors causing deterioration include deicing salts, corrosion, leaching, environment, traffic impact, reactive material and foundation settlement.

Cracking: A crack is usually defined as an incomplete separation of the concrete into two or more parts with or without a space between them. Different types of cracking can occur in a concrete structure and the significance of the crack depends on the structure type, crack origin and whether the width and depth increase with time. Cracks are common in concrete because of its low tensile strength and relatively large volume change that result from changes in humidity and temperature. Cracks can be categorized into several types, including, plastic shrinkage, drying shrinkage, settlement cracks, structural cracks and due to reacting aggregates, corrosion and freeze and thaw. Plastic shrinkage cracks are caused by rapid drying of concrete in its plastic state. The cracks are usually wide and shallow and spaced in regular intervals and may form a definite pattern. Plastic shrinkage cracks are worth noting but have little direct effect on the condition evaluation. Drying shrinkage cracks result during drying of restrained concrete after it has hardened. They usually are finer and deeper than plastic shrinkage cracks and have a random orientation. These cracks have little effect on the capacity analysis of the structure. Settlement cracks may be of any orientation and width, ranging from hairline cracks above the reinforcement; that result from subsidence of high slump concrete or from settlement of form work to wide cracks in supporting members; caused by settlement of the foundation. Slump caused cracks can cause deterioration and settlement cracks which are moving can be critical and effect the load carrying capacity of the bridge. Structural cracks can occur from differences between assumed and actual stress intensity including fine cracks controlled by provision of reinforcement. The width of the cracks varies, but the orientation is normally well defined. Longitudinal and diagonal cracks are examples for structural cracks which can be critical based on origin and extent. Corrosion cracks are associated with corrosion and occur over shallow covered reinforcement and the width of the cracks increase with time. The cracks normally terminate at the reinforcement. These cracks serve as indicators of loss of bond and loss of section. Map cracking is usually associated with chemical reaction between mineral aggregates and the cement paste. The number and width increase with time as the concrete is subjected to freeze and thaw action. Various reactions are possible although the most common reaction is between the alkalis of cement and the aggregate constituents that produce alkali-silica and alkali-carbonate reaction. Both types of this reaction result in serious damage to the concrete by causing abnormal expansion, cracking and loss of strength. Freeze/Thaw cracks are closely spaced cracks parallel to the concrete surface and only visible in cores and are usually associated with scaling.

Scaling: Scaling is the flaking away of the surface mortor of concrete. As the process continues the coarse aggregate particles are exposed and eventually become loose and dislodged. New concrete is particularly susceptible to scaling. However, weak surface layers resulting from improper finishes or concrete lacking air entrainment may flake away to limited depth. Scaling is primarily caused by repeated freeze and thaw action on the concrete. Very fine shallow surface cracking is usually evident. Areas where water puddle and the surfaces of the curbs and barrier walls are particularly susceptible to scaling.

Spalling: Spalling of concrete is generally recognized to be a serious defect. Spalling can cause local weakening, expose reinforcement, impair riding quality of the deck, and grow to such extent as to cause structural failure. The spall is a depression caused by the separation and removal of the concrete. Spalling is related to the age of the deck because the major causes of spalling are corrosion of the reinforcing steel, overstress and ice pressure. The amount of spalling increase with the age of the structure. Spalls are usually quite noticeable; however, in its early stage the spall may be a delamination and not noticeable. Cracks associated with spalling can be deep, wide and long and can reach the reinforcement and the prestressing steel.

Delaminations: Delaminations are separations along the plane parallel to the surface of concrete. Delaminations occur as the reinforcing steel expands and corrodes. As the corrosion process continues, increased pressure is exerted on the concrete and eventually the delamination becomes detached from the main body resulting in a spall. Cracks may or may not be present depending on the degree of corrosion and the amount of cover over the reinforcement. Bridge decks and corners of the beams are particularly susceptible to delaminations.

Leaching: Leaching is the accumulation of salt and or lime deposits; usually white in color, on the concrete surface. Water may carry lime from the cement to the concrete surface where the water evaporates leaving the deposit on the concrete surface. The most common locations where leaching is visible is the underside of the concrete deck and along cracks on vertical faces of abutments, backwalls and wingwalls.

Rutting: Rutting or the wheal track wear is a serious problem in asphaltic concretes but can be equally bad in cement concrete due to the action of moving traffic by the virtue of its deleterious effect on skid resistance. The problem involves the polishing or wearing of the coarse aggregates. Many limestone aggregates polish very fast and therefore not recommended for pavement surfaces. Studded tires constitute a major mechanical factor in pavement wear.

Structural Deformations: Usually in the form of differential settlement and collision damage. Differential settlement is one of the major causes for asphalt pavements failure and is of considerable threat for bridge decks besides collision damage, where usually the piers, footings, superstructure and the parapets are damaged by moving vehicles, both on the bridge and the waterway below. Differential settlement results due to the settlement of the structurally weak areas, subgrade, or the subbase from the constant impact and live moving loads from the vehicles. Cracks, deformations, bearing stresses, joint jams, potholes result depending upon the amount of stress involved and the duration of time. Good design, construction and through investigation of the foundation soil minimizes this problem.

Popouts: Popouts are small, conical shaped spalls on the surface of concrete that results from the excessive expansion of the relatively few aggregate particals near the surface. Popouts are a special form of freeze/thaw deterioration. In the absence of freeze/ thaw the offending particals are generally few in number and invariably very porous, light weight materials which tend to float to the top of the concrete where the relatively shallow concrete cover is not sufficient to withstand the pressure generated by the water freezing in them. Popouts are not considered as a serious threat to the integrity of of concrete and does not reflect on its strength loss.

Joint Deterioration: Joints in the bridge, also called expansion joints are made of different materials including organic and metal compounds and are designed to facilitate the expansion and contraction of the bridge deck due to temperature changes. Settlement, traffic impact, water leakage, wear of the joint material, loss and creeping are but some of the many which cause joint deterioration which usually results in ineffective utelization of the joint, thereby defeating the purpose for which it has been designed. Joint deterioration is serious and is accounted for in the condition evaluation of the deck.

2.2.1 Factors Causing Deterioration

The factors that can cause deterioration in reinforced concrete are many and varied. They include design details, construction, maintenance deficiencies, reactive materials, environmental conditions, corrosion of steel, wear, impact and overstresses caused by overloading or foundation movement. In order to properly evaluate the deterioration problem, its probable causes should be determined, [17][18][19][26][27].

Poor Design Details: Some design details that can cause concrete to deteriorate are insufficient expansion space or insufficient cover over the reinforcement. Also, the problem of drainage many times does not receive sufficient attention during design. Insufficient expansion space provided between ends of slabs, at expansion joints will cause spalling or compressive fracturing. Insufficient cover over reinforcement may cause corrosion of the reinforcing steel which in turn causes spalling or delaminations of the concrete. Lack of improperly placed drains may cause ponding on the concrete surface that result in scaling of concrete or early corrosion of reinforcement.

Construction Deficiencies: The construction deficiencies and construction operations that can result in deterioration of concrete are numerous. Some of the most common are noted in the following paragraph.

Improper Mixing: Addition of excess water to concrete during mixing or applying water to the concrete during finishing operations lowers the quality of the concrete making it susceptible to damage from freeze and thaw and traffic.

Over Working of Concrete: Overworking of concrete during finishing and the introduction of insufficient or excessive amounts of air entrainment admixture during mixing, also lowers the durability of concrete.

Poor Curing Practice: Poor curing practices that allow rapid loss of moisture from the concrete will result in shrinkage cracking and impair the strength and durability of the surface concrete.

Improper Slump: Excessive concrete slump can result in excessive subsidence of the concrete that can cause surface cracking over reinforcing bars.

Inadequate Support of Steel: Inadequate support of steel can result in movement of reinforcement as concrete is in the initial set stage, causing lack of bond or cracking above the reinforcing steel.

Improper Placement of Concrete: Allowing concrete to free fall during concrete placement in deep structures causes segregation and honey-combing in concrete.

Improper Placement of Steel: Improper placement of steel can result in inadequate cover and subsequent corrosion of reinforcement or serious misplacement can result in the component being below design strength. The weakened component may crack or fail under loading.

Lack of Foundation Investigation: Construction of piers and abutments on unsuitable soils may result in settlement which may in turn cause overstresses in the other concrete members.

Corrosion: The use of deicers has greatly increased the corrosion of reinforced steel. Even if there are no cracks, water permeates porous concrete. The water carries the deicing salt into the concrete and ultimately reaches the reinforcing steel. Salt in solution provides an electrolyte, and oxygen in the water provides the oxidizing agent. The resulting environment is ideal for the corrosion of steel. As the products of corrosion occupy considerably more volume than the parent material, tensile forces greater than the strength of concrete are exerted within the concrete. Cracking and Spalling result. And there can also be significant loss of section in the reinforcement that may reduce load bearing capacity of the structure.

Overstress: The most common cause for overstress is a load greater than the operating capacity. Concrete beams, girders and decks are all subject to damage under overstress conditions. Overstressing of beams and girders normally cause vertical or diagonal cracking. Wide extensive vertical cracks extent upward from the bottom near the center of simple beams or copious diagonal cracks at the end of simple beams indicate possible overstressing. Beams that are continuous over the support may develop vertical cracks extending downward from the top of the beam over the support. Cracking in concrete decks parallel to and over supporting elements indicate possible overstress.

Foundation Movements: Generally, foundation movement generate tensile stresses in substructure units. This tensile stress can cause serious cracking in the concrete structure. Changes in the alignment or grade of of the bridge superstructure and the width of the joint openings are also symptoms of foundation movements.

Temperature: Freezing and Thawing are common causes of concrete deterioration. Porous concrete absorbs water and when water freezes, high expansive pressures are created because of the larger column created by ice formation. These pressures often produce cracking, spalling, or scaling. Aggregates such as chert, with lower coefficient of expansion than cement paste may also cause high tensile stresses, resulting in cracks and spalls. Concrete expands at a rate of 5.5 millionths of an inch per degree fahrenheit rise in temperature. If concrete is prevented from expanding or contracting because of friction or because it is being held in place, the slab will crack under tension.

Chemical Attack: Deicers include chloride ions which ultimately reach the reinforcing bars and cause corrosion of steel. As the products of corrosion occupy considerably more volume than the parent metal, tremendous pressure is applied to the concrete from within, causing cracking and spalling of the concrete. Ammonium and magnesium ions react with calcium in cement. Calcium and sodium and sodium sulphates will react with the tricalcium aluminate in the cement paste. Acids will attack the cement paste and chemically transform the paste composition. The common symptoms are scaling, spalling, random cracking, parallel cracking and swelling in compressed members and exposed aggregate.

Traffic Impact: Few elements on the bridge escape impact or collision. Trucks, cars, ships and barges often strike piers, over head beams and railings. Damage can range from scarring of concrete to severe spalling and cracking, or complete destruction of the member. The impact may severe the tension reinforcement impairing the load capacity of the unit. Wear or abrasion in traffic lanes can result in scaling in traffic lanes and raveling and cracking at joints. Snow removal equipment and sweepers scar curbs and parapets.

Reactive Materials: Reactive aggregates, high alkali cement, and contaminated mixing water cause serious deterioration of concrete. The symptoms of such deterioration are swelling and cracking, unsound concrete and popouts. After a few years of being exposed to weather, concrete that was made using reactive materials will begin to crack over the entire surface and appears to be expanding. As the deterioration progresses, the concrete will begin to crumble and disintegrate.

2.3 Condition Evaluation

Figure 6, page 24 is the Structure Inventory and Appraisal Sheet which is used by many state agencies to inventory and evaluate the structural condition of the bridge. There are 90 items described in the sheet and modified versions of the same are available and being used by different states to suit their own policies and requirements. Concrete/Reinforced concrete is the major material and the deck is the major item [item 58], whose condition is critical to the structural operating and inventory rating of the bridge. Deck, as said before, is that single item component which has deteriorated the most and all the different deterioration defects found in the deck are also found in the remaining parts of the bridge but, only to a minor extent.

A specialized table for bridge deck evaluation and to find the condition rating is given in Figure 7, page 25

The condition indicators or the defects causing deterioration that are identified are only a few and as claimed, a more flexible and detailed guide is required to evaluate condition of the bridge deck using other uncovered condition indicators.

Figure 8, page 26 show the condition ratings and the equivalent description of the rated conditions.

STRUCTURE INVENTORY & APPRAISAL SHEET

Revised 12-78

IDENTIFICATION

- State
- Hwy District
- County ____ City/Town
- Inventory Route ____ On ☐ Under ☐
- Features Intersected
- Facility Carried by Structure
- Structure No ____ 1 of
- Location
- Min. Vert. Clearance, Inv Rte.
- Milepoint
- Road Section No
- Defense Bridge Description
- Defense Milepoint
- Defense Section Length
- Latitude
- Longitude
- Physical Vulnerability
- By pass, Detour Length
- Toll
- Custodian
- Owner
- F A P No

CLASSIFICATION

- Highway System
- Administrative
- Functional

	By	Date
Transfer of Data		
Maintenance Insp		
Condition Analysis		
Appraised		
Cost Estimate		
General Rence		

STRUCTURE DATA

- Year Built
- Lanes on Str ____ under
- ADT ____ Year
- Design Load
- Appr Rdwy Width (Shld)
- Br Median ☐ None ☐ Open ☐ Closed
- Skew
- Structure Flared ☐ Yes ☐ No
- Traffic Safety Features
- Navigation Control ☐ Yes ☐ No
- - Vertical ____ ft
- - Horizontal ____ ft
- Open, Posted, or Closed
- Type Service (Code)
- Structure Type - Main
- - Approach
- No of Spans - Main
- - Approach
- Total Horiz. Clearance ____ ft
- Max Span Length ____ ft
- Structure Length ____ ft
- Sidewalk Lt ____ ft, Rt ____ ft
- Br Roadway Width (curb-curb) ____ ft
- Deck Width (out-out) ____ ft
- Vert Clearance over Deck ____ ' ____ "
- Underclearance - Vertical ____ ' ____ "
- Lateral Right ____ ft
- Left ____ ft
- Wearing Surface

CONDITION

	Material	Condition Analysis	Rating (0-9)
Deck			
Superstructure			
Substructure			
Channel & Channel Protection			
Culvert & Retaining Walls			
Estimated Remaining Life		Approach Roadway Alignment	
Operating Rating		Inventory Rating	

APPRAISAL

	Deficiencies	Rating (0-9)
Structural Condition		
Deck Geometry		
Underclearances - Vertical & Lateral		
Safe Load Capacity		
Waterway Adequacy		
Approach Roadway Alignment		

PROPOSED IMPROVEMENTS

- Year Needed ____ Completed ____ Describe (item 75)
- Type of Service
- Type of Work
- Improvement Length ____ ft
- Design Loading
- Roadway Width ____ ft
- Number of Lanes ____ Prop Rdwy Improvement - Year
- ADT ____ Year ____ - Type
- Cost of Improvements $ ____ 000
- Prel Engrg $ ____ 000
- Demolition $ ____ 000
- Substructure $ ____ 000
- Superstructure $ ____ 000
- Insp Date

Remarks:

Figure 6. Structural Inventory and Appraisal Sheet.

		Condition Indicators (% deck area)			
Category Classification	Rating	Spalls	Delaminations	Electrical Potential	Chloride Content #/CY
Category #3 Light Deterioration	9	none	none	0	0
	8	none	none	none >0.35	none >1.0
	7	none	<2%	45% <0.35	none >2.0
Category #2 Moderate Deterioration	6	<2% spalls <u>or</u> sum of all deteriorated and/or contaminated deck concrete <20%			
	5	<5% spalls <u>or</u> sum of all deteriorated and/or contaminated deck concrete 20 to 40%			
Category #1 Extensive Deterioration	4	<5% spalls <u>or</u> sum of all deteriorated and/or contaminated deck concrete 40 to 60%			
	3	>5% spalls <u>or</u> sum of all deteriorated and/or contaminated deck concrete >60%			
Structurally Inadequate Deck	2	Deck structural capacity grossly inadequate			
	1	Deck has failed completely Repairable by replacement only			
	0	Holes in deck - danger of other sections of deck failing			

Figure 7. Concrete Bridge Deck Evaluation.: FHWA condition rating matrix.

Rating	Equivalent Rating Conditions Descriptions 1978	1972
N	Not applicable	Not applicable
9	New condition	New condition
8	Good condition - no repairs needed	Good condition - no repair necessary
7	Generally good condition - potential exists for minor maintenance	Minor items in need of repair by maintenance forces
6	Fair condition - potential exists for major maintenance	Major items in need of repair by maintenance forces
5	Generally fair condition - potential exists for minor rehabilitation	Major repair - contract needs to be let
4	Marginal condition - potential exists for major rehabilitation	Minimum adequate to tolerate present traffic, immediate rehabilitation necessary to keep open
3	Poor condition - repair or rehabilitation required immediately	Inadequacy to tolerate present heavy load - warrants closing bridge to trucks
2	Critical condition - the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete.	Inadequacy to tolerate any live load - warrants closing bridge to all traffic
1	Critical condition - facility is closed. Study should determine the feasibility for repair	Bridge repairable, if desirable to reopen to traffic
0	Critical condition - facility is closed and is beyond repair	Bridge conditions beyond repair - danger of immediate collapse

Figure 8. Condition Ratings and Equivalent Condition Description.

2.4 Failure Analysis

Failure is defined as the loss of ability to perform specific function by a component or an arrangement [1]. In most products and systems where the product has an well to do and established failure pattern, failure analysis is not performed. However, in new designs and established products such as the bridge, when uncertainties exist, failure analysis is often required to;

1. Obtain a better understanding of the failure event and its causative factors
2. Develop remedial actions for the prevention of failure recurrence
3. Establish responsibility for the failure and for the remedial action

Failure analysis has been performed as an after the fact analysis all these years and the objective has been to identify and isolate the cause of failure so that remedial or preventative action could be instituted. Failure analysis helps assign the failure cause to the deficiency occurring in either the design, production/construction or the end use environment. These areas correspond to the different phases in the life cycle of the system during which failure analysis can be performed. User related failures usually occur when normal operating life is exceeded or abnormal operational stresses or maintenance related stresses exceed design strength in the use environment. Failure analysis techniques originated and is extensively used in all stages of production in factories producing mechanical and automotive consumer goods such as automobiles, electronic components and aeroplanes. Failure analysis is equally applicable and can be used with a fair degree of certainty in the civil engineering profession, such as in the analysis of structural stability of multistoried structures, parking lots and bridges. The basic idea behind the investigation and analysis in either of the industries remains the same except that in structural components, for most of the time the failure of a component is less catastrophic and is not instantaneous. Rather it is continuous, like in deterioration failure, due to the fact that structures are most of the time designed as parallel systems and incorporate a large degree of redundancy and a factor of safety to see that failure does not cause casualties. But, the effects of failure is often undetected and can cost a fortune in maintenance and repair, once discovered. Occasions where structural failures have been instantaneous and often accompanied with dramatic and drastic results, involving complete destruction of property and life is not rare, like in the case of earthquakes and faulty designs.

Failure Analysis Techniques such as Destructive Physical Analysis, Fault Tree Analysis, Failure Mode Effects Analysis, Single Point Failure Analysis, Functional Failure Analysis etc., find application in design, research and in the after-the-fact analysis activities. And, with some techniques finding wider use in specific areas like; Failure Mode Effects Analysis in the design stage, and Fault Tree Analysis in the after-the-fact analysis stage, even though both of them are equally good in any given level of investigation.

2.4.1 Failure Mode Effects Analysis [FMEA]

Is a powerful tool which helps in analyzing failure to:

- Improve the design reliability of the failed component
- Improve control the reliability factors in construction, installation and in the preventive maintenance program.

FMEA is an inherent element in the reliability modeling and prediction process which is also concerned with effects of failure. The effects of all failures in terms of the impact on the system reliability, safety and performance is not the same and therefore there is a need to rank the relative importance of the criticality of each failure. To satisfy this need the Criticality Analysis Factor was added to the FMEA process and thereby caused the FMECA or the Failure Mode, Effects and Criticality Analysis. In the bridge system four potential failure modes are identified.

1. Structural Instability
2. Structural Failure

3. Foundation Movement

4. Differential Settlement

The topic of the study is Structural Instability caused by deterioration and since this failure is in itself quite considerable, only structural instability is considered for further analysis. Therefore, the question of criticality analysis does not arise and hence only the FMEA is applied. FMEA is thorough, simple and straight forward. It is also flexible because there is no sealing regarding the scope or the depth of the analysis. Here, FMEA is tailored to serve the cause of maintainability, repair and rehabilitation of bridge components and is confined in scope to act as an input to the Fault Tree Analysis. A consensus on a standard methodology to perform FMEA does not exist. However, two standards have been issued. Computer programs for the automation of the FMEA are available, but not suitable for the present needs of a bridge analysis and only exist for the aerospace and other automotive industries [1]

Methodology - Systems Approach: The approach can be TopDown Analysis, which begins at the bridge system level failure modes and continues through the lower successive levels, or the BottomUp approach, beginning at the lower level or any part level and working toward the top is available. A combination of approaches can be tried too.

Analysis Method: Can be Functionally Oriented Analysis or Hardware Oriented Analysis or a combination of both. The functional method identifies the functions of the system elements as outputs which are listed and their failure modes and effects analyzed at the functional level independently of the detailed hardware design.

Failure Modes: The number and types of failure modes to be addressed at each level of analysis is to be decided based on adequacy and the refinement aimed to be achieved. These factors are governed by the availability of expert knowledge of the persons conducting the analysis and the time and cost factors.

Multiple Failures and Failure Detection: Significant decision concerns the practices followed to detect failures and the potential multiple failure situations. FMEA excludes multiple failure situations because the number of possible failure combinations make it totally impractical. It does not however, exclude the dependent failures, which may occur as a result of a single failure.

FMEA Worksheet Layout: Standard worksheets are available. Indigenous and simple worksheets can be used at different levels of the analysis based on the type of problems addressed and the relative newness of the field like in the case of this particular study.

The work sheet should have

- *Headings*
- *Identification Number*
- *Nomenclature*
- *Item*
- *Function*
- *Failure Modes*
- *Causes*
- *Failure Effects*
- *Probabilities of Failure*
- *Failure Detection*
- *Severity Classification*
- *Remarks*

2.4.2 Fault Tree Analysis [FTA]

FTA, [1][3] originated in the aerospace industry in the 1960s when logic diagrams and Boolean algebra were used to represent and summarize the different events which can lead to a specific unspecific undesired event. FTA is a simple and effective tool for general use in risk assessment, single and multiple failure analysis. FTA can be used to develop qualitative and quantitative probabilistic reports, all though the lack of quantitative data is a difficult problem for FTA in the same way as to the FMEA. FTA is most applicable in the initial phases of the system life cycle but is also useful at any time. FTA uses symbolic logic diagrams to show the cause and effect relationships within a system between a specified top level undesired event and all of its possible contributing causes. The contributing causes need to be limited to the system failures and may include other events such as accidents. FTA is a result of deductive logic and can be developed manually or by using automated draft techniques using modern computer aided design systems. When the FTA diagram is expanded the contributing events themselves would be the end events of the subordinate contributing events.

The diagram and the analytical process begins with the identification of undesired top level event. The top undesirable event may be a system failure event or any other event which may have multiple failure causes requiring analysis. Using deductive logic the top undesired event is connected to all the contributing causative events in a manner which depicts its interrelationship. The lower level events can be considered as inputs to the upper level event. Completed FTs can be combined with probabilistic data for the purpose of establishing the relative criticality of the system failures which can be difficult to access in comparison with the criticalities of the FMEA. The multiple failure causing events introduce new and complex conditional probabilities which may not be represented in the total single failure rate. Therefore, FMEA can be an important supplement to the FTA.

3.0 MODEL DEVELOPMENT

From the previous discussion it is clear that a methodology consisting of different systems and analytical techniques or models interacting with one another, where the output of one is the input for the next is found necessary to investigate bridge deck deterioration.

3.1 Objective

The objective of the model is to develop a methodology to investigate bridge deck deterioration by identifying all the basic events causing defects which influence deterioration rate, and to develop a probable range of reliability any given time during the service life of the bridge deck.

The definition does not confine to a single bridge or to a single type of concrete bridge. Instead the methodology is applicable to all types of concrete bridges in service all over the country and exposed to diverse and varied climatic and environmental conditions throughout the year.

3.2 Methodology and Modules

1. FMEA Module
2. FTA Module
3. Special Tables
4. Condition Index V/S Service Life Graph or Deterioration Module
5. Decision Tree

A description of each module is given below:

3.2.1 Failure Mode, Effects Analysis [FMEA],

Tables 2 to 4, pages 35 to 37 : It has been understood that FMEA is a powerful and useful tool in the design, production, construction and maintenance stages of a product cycle to isolate and analyze the problem area, [1][2][9][17][18]. FMEA finds extensive usage in the design stage but is equally good in the end use stage also. FMEA becomes effective and refined should the the criticality of each failure mode and its associated causes are investigated thoroughly with the required precision and time. FMEA in its basic format is a simple table where the system, subsystem and components are identified depending on the desired level of investigation and importance of any particular item from the safety point of view. The function of each item, failure mode, effects and the associated causes are identified including failure detection and mitigation. Many different standardized formats are available and find specific use in the automotive industry more than in the civil/construction industry. Since there is no specific format in the civil engineering industry, here an attempt is made to develop an applicable format to help fulfill the desired objective in this study. The headings found most suitable for the purpose are 1) Item, 2) Related Components, 3) Failure

Modes of Components, 4) Failure Effects, 5) Failure Causes, 6) Failure Mitigation and 7) Failure Detection.

Less importance is attached to look at the FMEA from the systems point of view. Both TopDown and Bottom-Up approaches are discarded and instead the emphasis is on the functional analysis without consideration for hardware arrangement in the bridge. For example, Table 2, page 35 a general item, Reinforced concrete, is chosen, and its failure mode and effects described. In this way many unwanted and cumbersome repetitive description with regards the many components with the same material, function and failure modes despite varied shapes and sizes is eliminated. A significant omission from the standard format is the criticality analysis of each failure mode. The reason is, even though four significant failure causes are identified only structural instability due to deterioration is isolated for further analysis, which is the topic of this study. Also, the priori probabilities for the various failure modes is unknown and the criticality based on probability values cannot be ascertained. The ultimate objective of the study being; to develop failure probability ranges due to deterioration alone, the following limitations and assumptions regarding FMEA are made.

3.2.1.1 Limitations:

1. FMEA is a generalized methodology identifying the failure mode and effects of the items discussed and the information made available is considered as an input to the FTA.
2. Gives macroscopic view of the failure mitigation processes without discussing the suitability of one over the other for repair and maintenance purposes.

3.2.1.2 Assumptions:

1. Designed to provide information input to the FTA.
2. Itemization of components regardless of the actual arrangement, in the bridge system, but based on common failure modes.
3. A single failure mode; structural instability, is considered for further analysis. Hence criticality analysis of failure modes sacrificed.

Table 2. FMEA Table for Deck Slab. Structural Instability is one of the deck failure modes and Deterioration is one the causes.

ITEM(S)	COMPONENTS	FAILURE MODES	FAILURE EFFECT(S)	FAILURE CAUSES	FAILURE MITIGATION	FAILURE DETECTION
• Concrete and • Reinforced Concrete	• Deck Slab • Floor Beams • Sidewalks • Curbs • Railings • Bent Caps • Bents • Columns • Piers • Footings • Wingwalls • Beam/Column connection • Approach/ Bridge Seat	Structural Instability	Component Failure	• Deterioration • Inadequate design • Material quality • Construction practice	• Design • Construction • Material • Maintenance • Repair • Rehabilitation • Strengthening • Replacement	• Visual Techniques • Nondestructive Tests - Rebound & Penetration Tests * Schmidt hammer * Windsor Probe - Sonic Methods * Delamtect * Chain drag * Sounding rods - Ultrasonic Techniques - Electrical Methods * Half Cell Potential Test - Nuclear methods - Thermography * Infrared - Radar * Ground Penetrating - Air Permeability • Destructive tests - Concrete Strength - Steel Strength - Weight Loss - Pit Depth - Carbonation - Moisture Content - Endoscopes - Con. Permeability
		Structural Failure	Component Failure Subsystem Failure System Failure	• Overloads • Seismic forces • Foundation movement	• Speed Posting • Reduced Traffic • Reduced Axle-loads	
		Foundation Movement	Component Failure Subsystem Failure System Failure	• Change in watertable Soil Settlement/ volume change • Shear Failure • Flooding Channel Shifting • Erosion	• Soil Stabilization • Channel protection • Improved channel flow • Anchoring	
		Differential Settlement	Subsystem Failure System Failure	• Expansive Soils • Foundation on differential substrata • Movement and dissolution of substrata	• Soil Stabilization • Anchoring • Reduced Traffic and Axle loads • Speed Posting	

Table 3. FMEA Tables for Expansion Joints & Bearings. Joint deterioration is significant in deck condition evaluation.

ITEM(S)	COMPONENTS (TYPES)	FAILURE MODES	FAILURE EFFECT(S)	FAILURE CAUSES	FAILURE MITIGATION	FAILURE DETECTION
* Joint	* Open * Sealed * Metal protected * Sliding * Finger	* Inadequate Deck slab movement	Component Failure Subsystem Failure	* Joint deterioration * Joint Design * Construction * Material * Constrained movement * Stepping	* Design * Construction * Material * Maintenance * Repair * Rehabilitation * Replacement	VISUAL INSPECTION
* Bearings	* Metal - Sliding Plate - Rocker - Roller * Elastomeric - Pads - Pad with Steel lining	* Inadequate Transverse, Rotational movement of Super-structure	Component Failure Subsystem Failure	* Bearing deterioration * Selection * Installation * Material * Skewed alignment	* Design * Selection * Installation * Material * Maintenance * Repair * Replacement * Rehabilitation	VISUAL INSPECTION

Table 4. FMEA Table for Foundation. Not significant in deck condition evaluation.

ITEM(S)	COMPONENTS	FAILURE MODES	FAILURE EFFECT(S)	FAILURE CAUSES	FAILURE MITIGATION	FAILURE DETECTION
* Foundation	* Abutment Foundation * Substructure foundation	Foundation Movement	Component Failure Subsystem Failure System Failure	* Change in watertable Soil Settlement/ volume change * Shear Failure * Flooding Channel Shifting * Erosion * Accident impact	* Soil Stabilization * Channel protection * Improved channel flow * Anchoring * Slope protection * Bank protection	SAME AS TABLE 2
		Differential Settlement	Subsystem Failure System Failure	* Expansive Soils * Foundation on differential substrata * Movement and dissolution of substrata	* Soil Stabilization * Anchoring * Reduced Traffic and Axle loads * Speed Posting	

3.2.2 Fault Tree Analysis [FTA]

Figures 11 to 30, pages 42 to 61: FTA, like FMEA, is an important and useful tool / technique finding extensive use in the automotive and mechanical industries and which has little or no application in the civil and construction industry. FTA is an graphical technique which gives clear and vital information on the events causing failure of system, subsystem and components. A BottomsUp approach is applicable here where in the basic events at a lower level cause or influence the event in the upper level. The effect is carried up to the top event which is called the undesired event, since this event culminates in failure due to action of the events occurring at the lower level. Failure here, is perceived as the inability of the top event to perform or maintain the desired level of serviceability or function [1][2][3][19][25].

FTA can be done independently of the the FMEA or in combination, to enlarge the scope of analysis and to gather as much as information as possible about the system, subsystem and component failure to reinforce the analysis of the particular problem.

3.2.2.1 Notations: Figures 9 and 10, pages 40 and 41:

Different geometrical figures are used as notations to represent different events. **Connectors,** which are geometrical figures are used to link the upper level events to the lower level events. These connectors are called **Gates. Straight Lines** are used to connect the entire tree. The tree branches and spreads toward the lower end and there can be many trees for many different failures modes of different components within a subsystem. The **Rectangle** is used to define any event represented by a gate. A **Circle** indicates a basic event or the lower most event which is not available for further analysis. Any event for the matter can be considered as a basic event to reduce unwanted analysis which does not help the desired objective. A **Polygon** with six sides is called a house event which may be occurring or not occurring. A house event can be considered as an indirect influence on failure which is not available or required for immediate analysis but only worth mentioning. A **Diamond** indicates an undeveloped event which may or may not develop in the future. The figure with parallel straight lines and bounded by semi-circles on both sides is called a **Conditional Event** which is used with an inhibit gate. **Triangles** are used as connectors or as transfer symbols to continue the analysis on a new page. An **And** gate is used to indicate that if all the lower events, also called input events, occur simultaneously, the top level event or the output event occurs. A **Priority And** gate indicates that output event occurs if all the input events occur in the order from left to right. **M out of N** gate, output event occurs if "m" input events out of "n" events occur. **Or Gate**; output occurs if one input event occurs. **Exclusive Or** gate, output occurs if one but not both events occur. **Inhibit Gate**, output event occurs when input conditional event occurs.

3.2.2.2 Assumptions:

1. The defects or events occurring in the second level in Figure 12, page **43** are the most important events and are of immediate concern in the deterioration analysis. While the rest of the events occurring lower to it are of importance only from the literary point of view and are important only when investigating the defects to find remedies, as to reduce their occurrence in the future and as such is of considerable interest to those doing experimental analysis only.
2. Events are identified by a numbering code in the connectors. Connectors with are numbered are called transfer symbols.

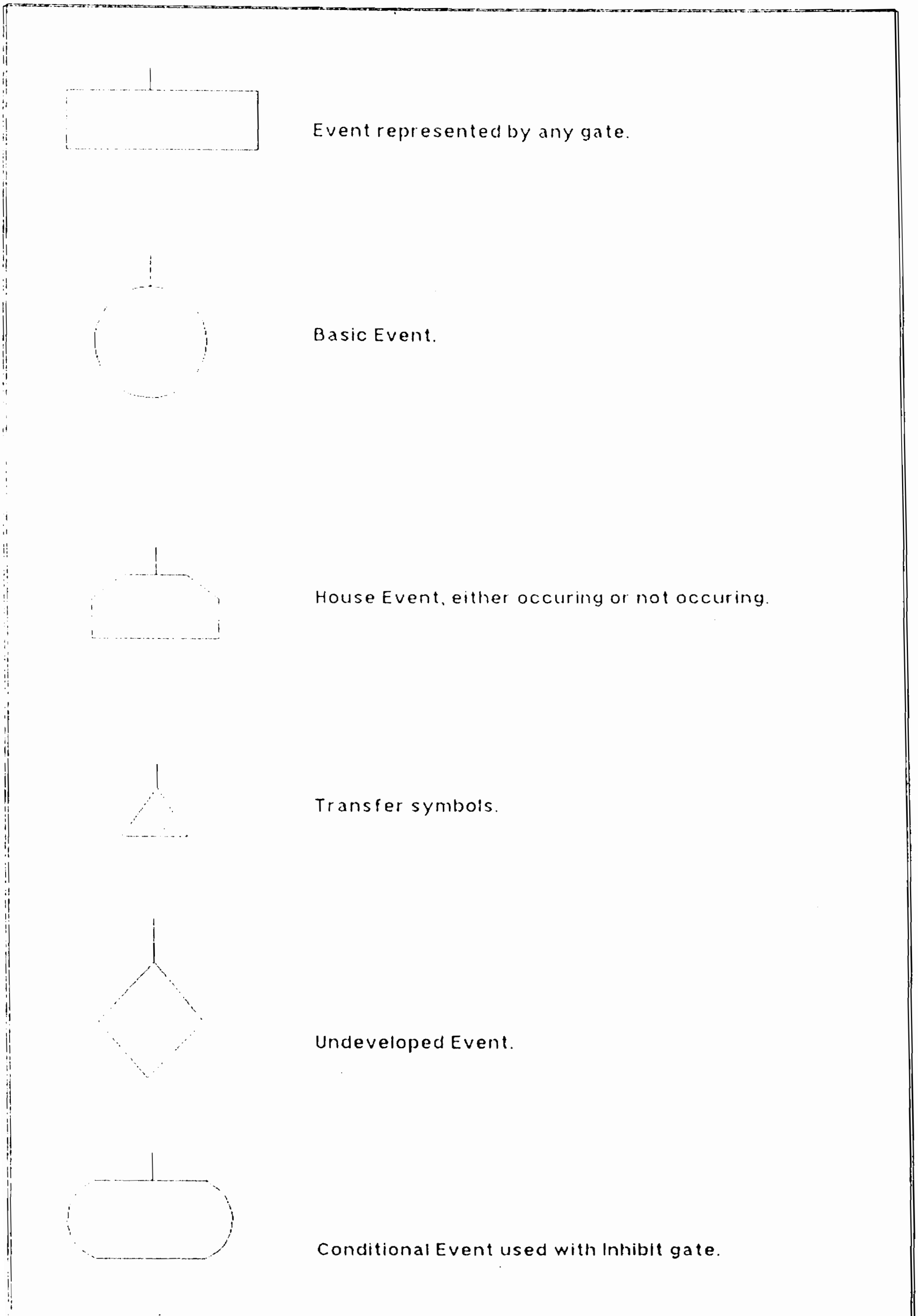
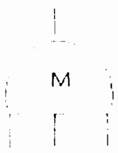


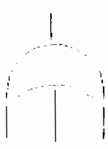
Figure 9. FTA Notations.

AND Gate, output occurs if all input events occur

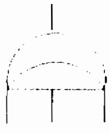
PRIORITY AND Gate, output event occurs if all the input event occurs in the order from left to right.



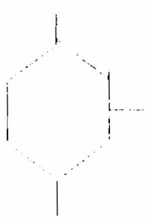
M out of N Gates, output occurs if 'm' out of 'n' input events occur.



OR Gate, output event occurs if any one of the input occurs.



EXCLUSIVE OR Gate, output event occurs if one but not both of the events occur.



INHIBIT Gate, output event occurs when input conditional event occurs.

Figure 11. FTA Notations, continued.

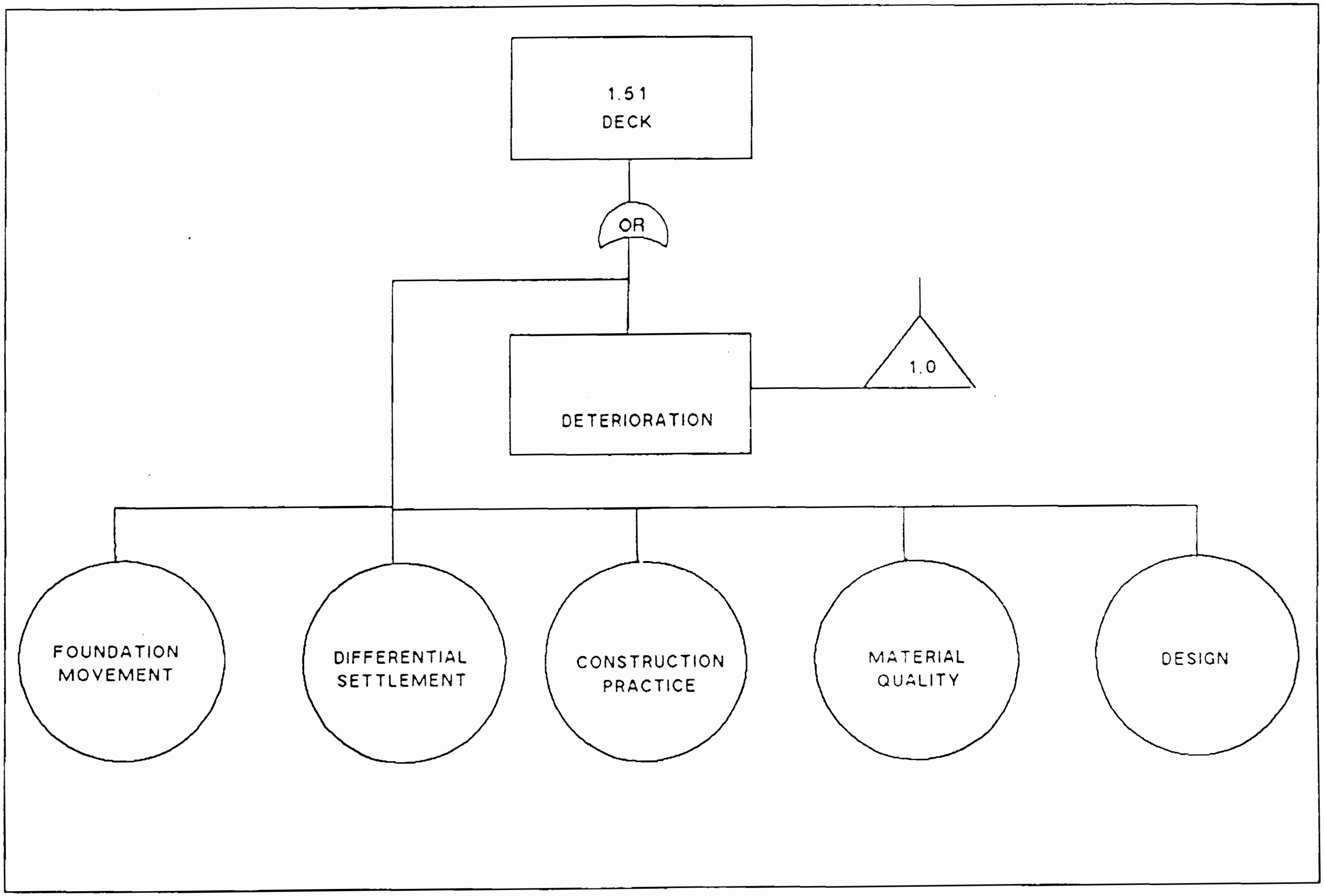


Figure 12. FTA of the Deck.: Only Deck Deterioration is considered for further analysis

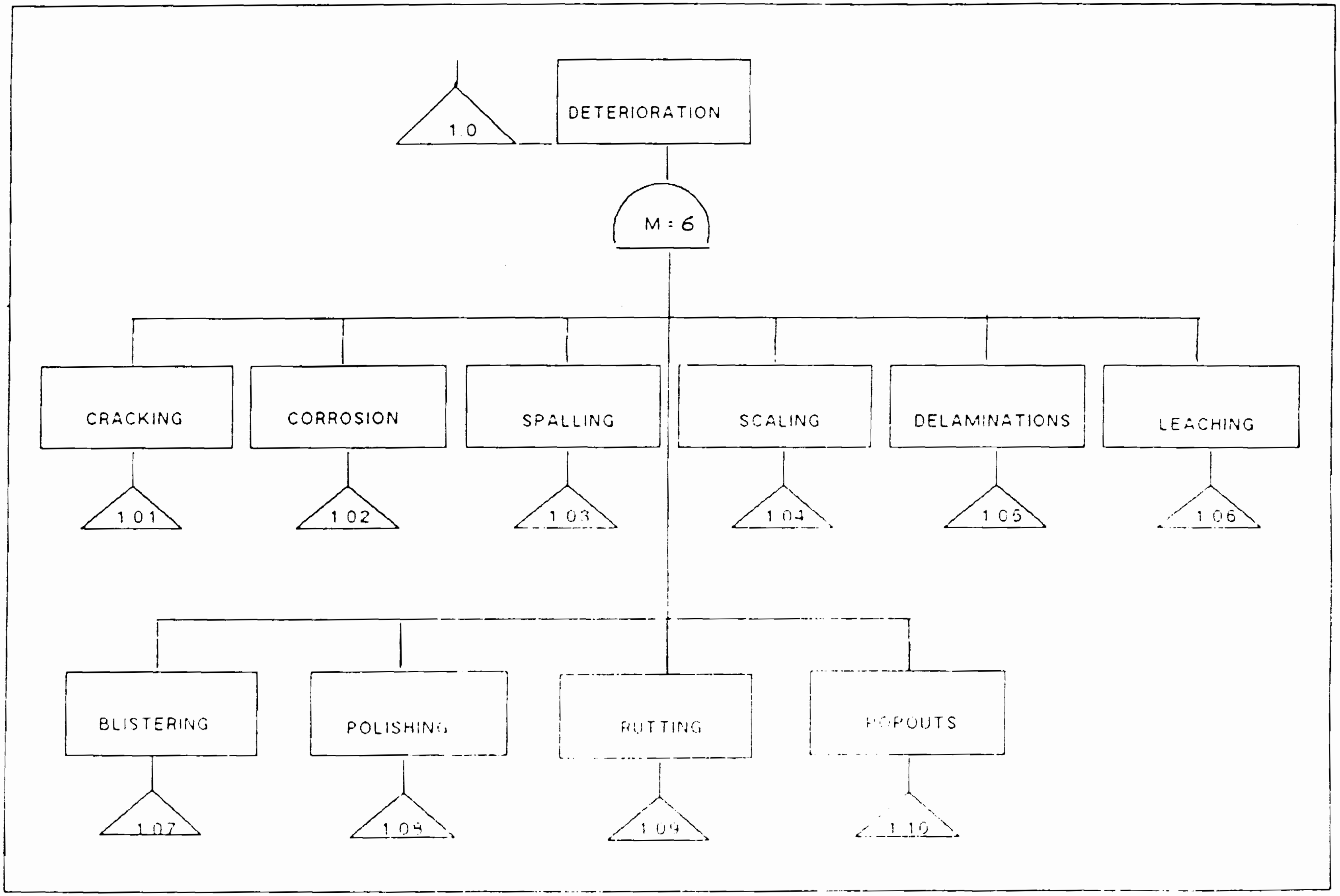


Figure 13. FTA, Defects causing Deck Deterioration.: In the subsequent figures, FTA further identifies the types of defects and the factors causing the defects.

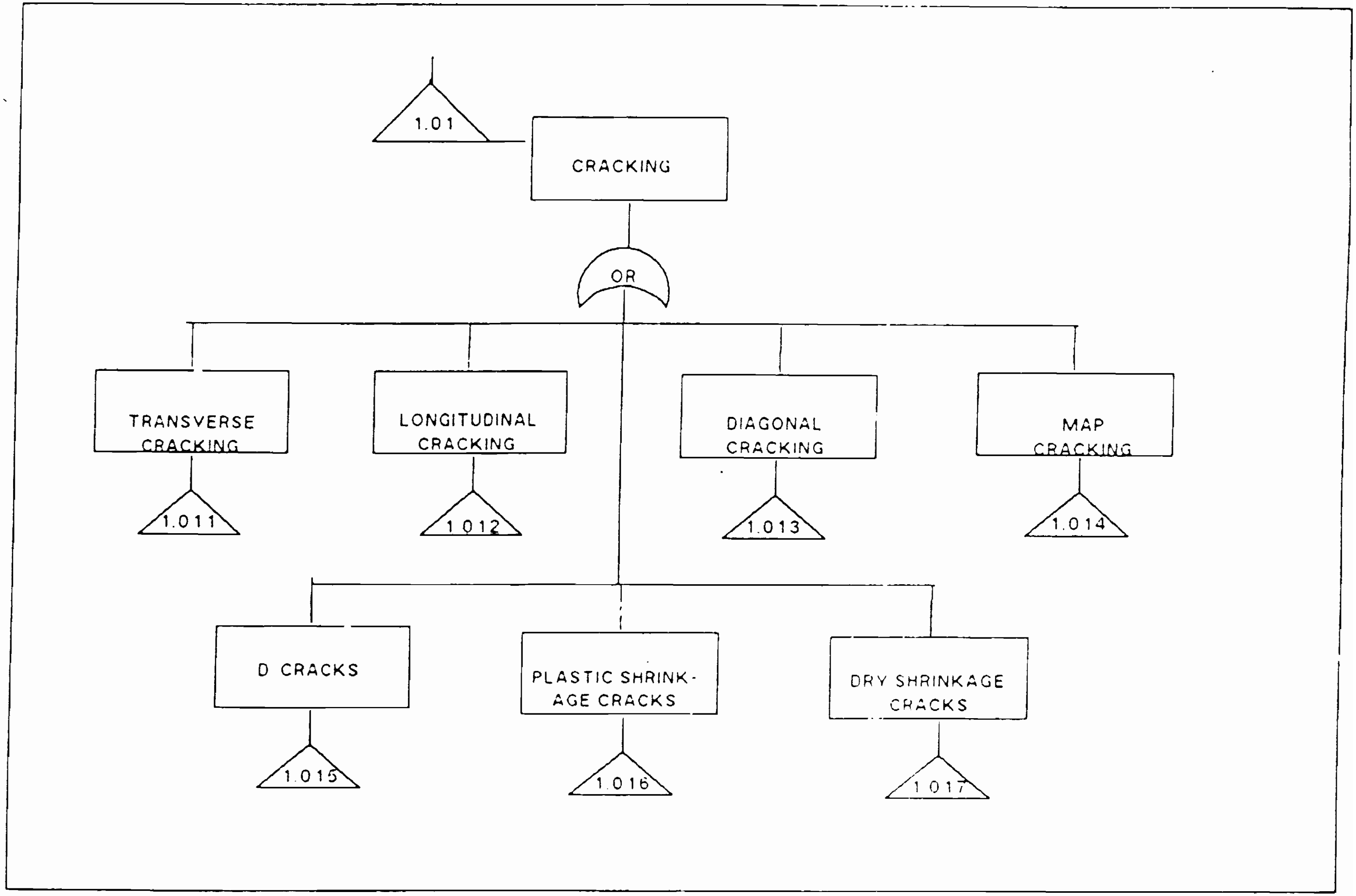


Figure 14. FTA, Cracking Defect and Types.

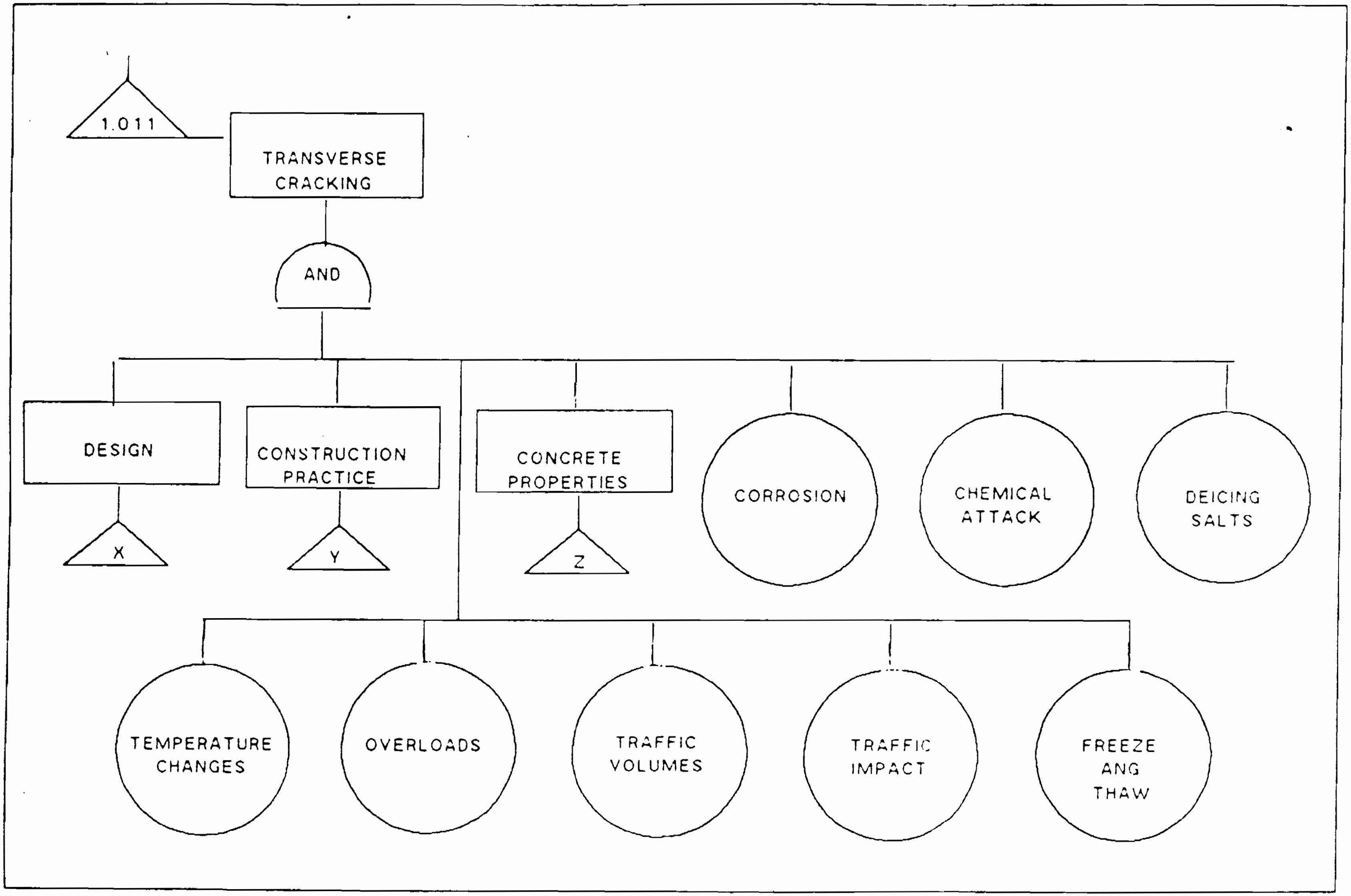


Figure 15. FTA, Cracking - Transverse and its Factors.: The factors contributing to transverse cracking holds good for vertical, diagonal, horizontal and map cracking also.

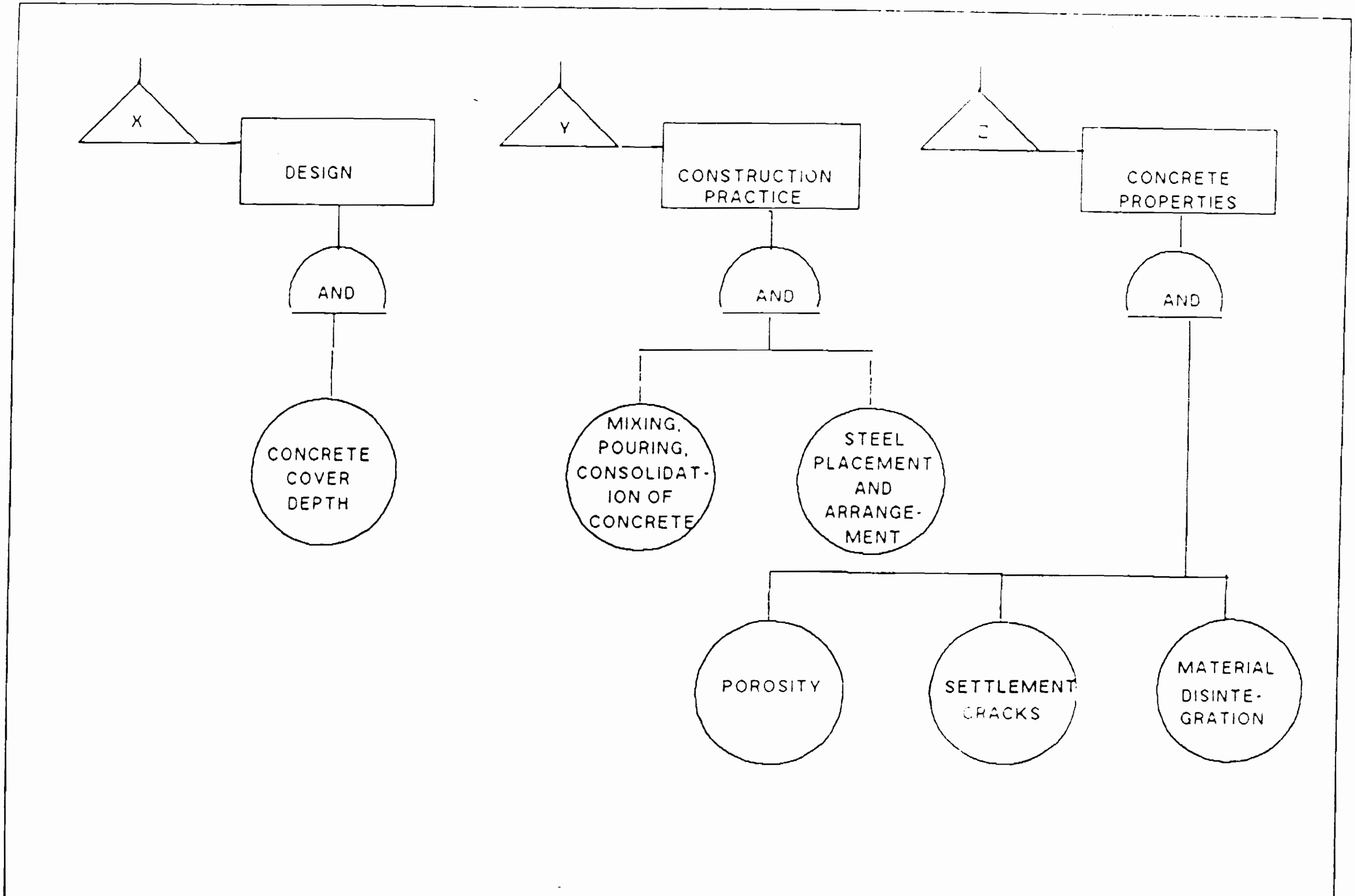


Figure 16. FTA, Analysis of Factors Causing Transverse Cracking.: The same holds good for the rest of the crack types described in Fig. 14.

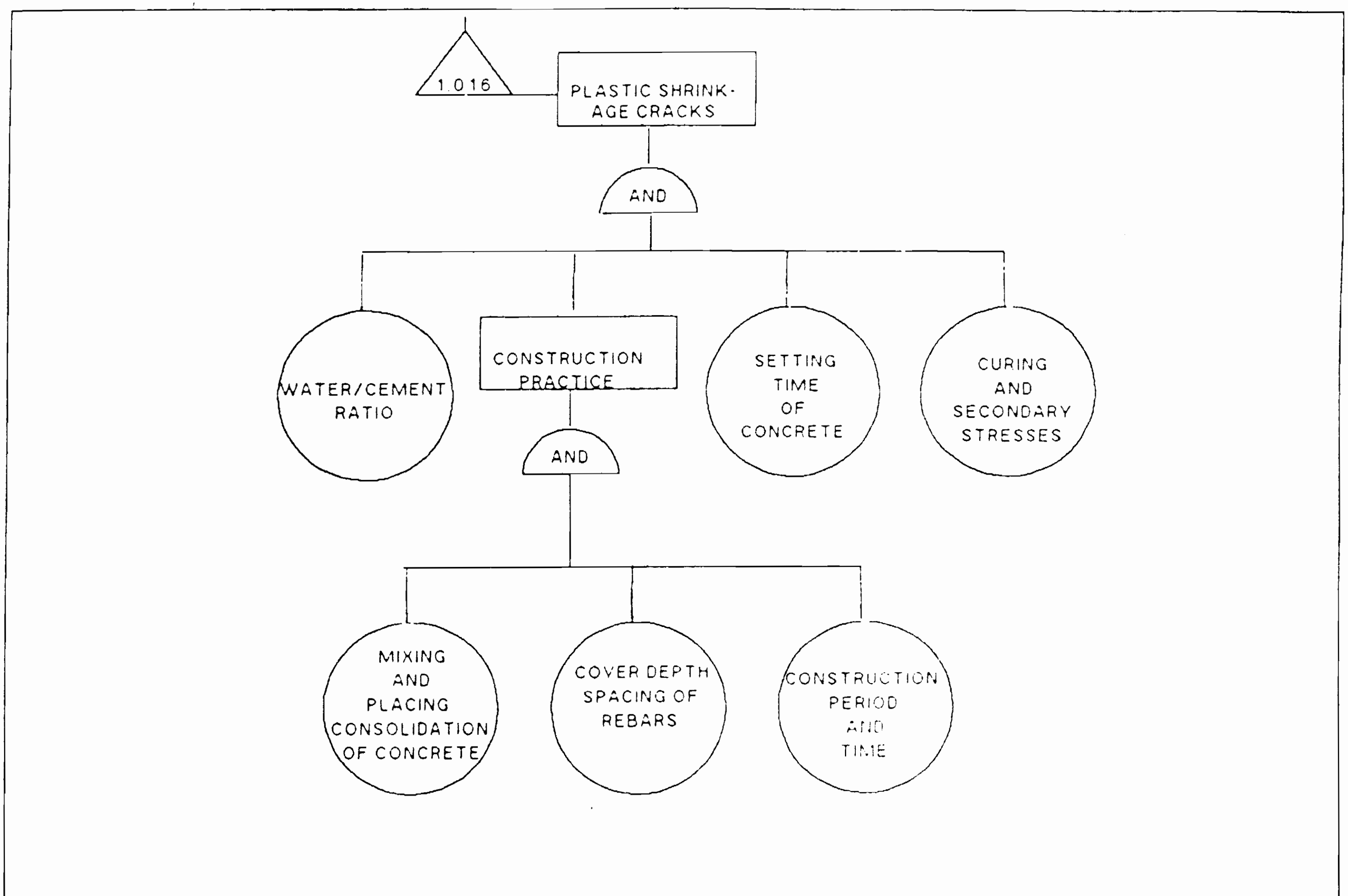


Figure 17. FTA, Cracks - Plastic Shrinkage.: Plastic Shrinkage Cracks and contributing factors.

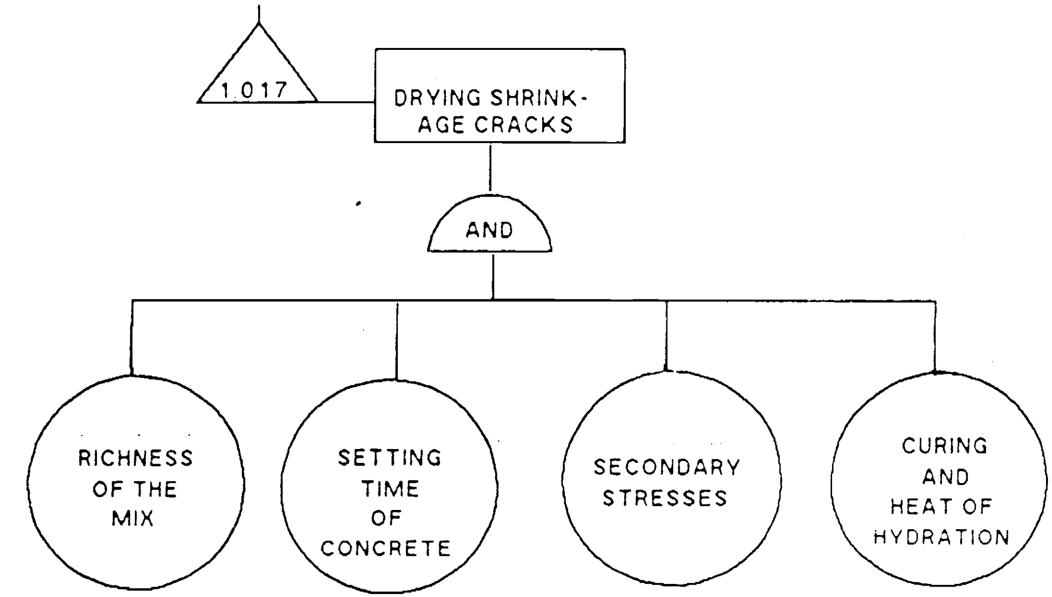


Figure 17. **FTA, Drying Shrinkage Cracks.:** Drying Shrinkage cracks and Plastic Shrinkage cracks are considered insignificant in condition evaluation of the deck and hence not accounted.

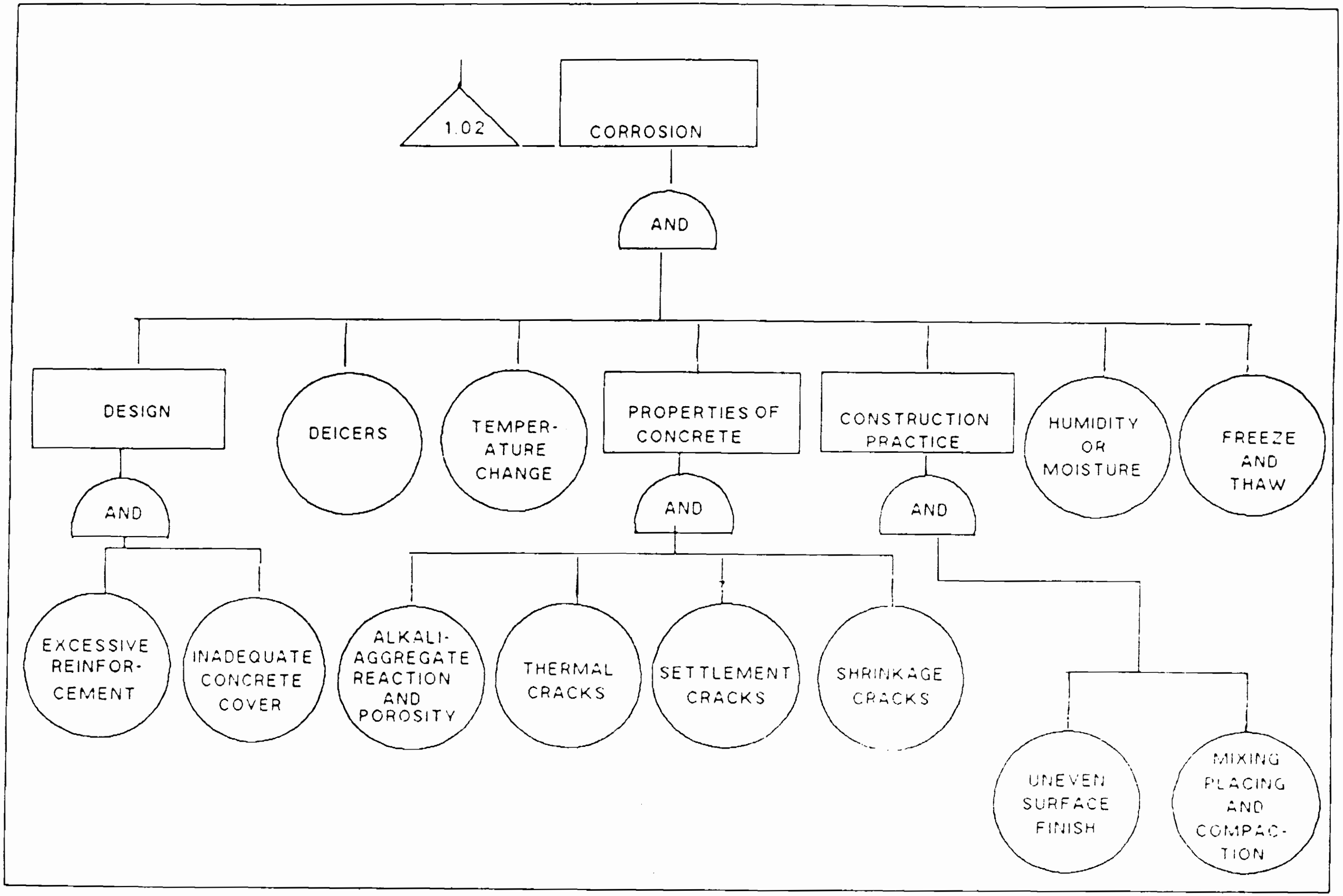


Figure 19. FTA, Corrosion and Factors.: Corrosion is considered both as an indicator for deterioration and as a factor for other forms of deterioration such as Spalling.

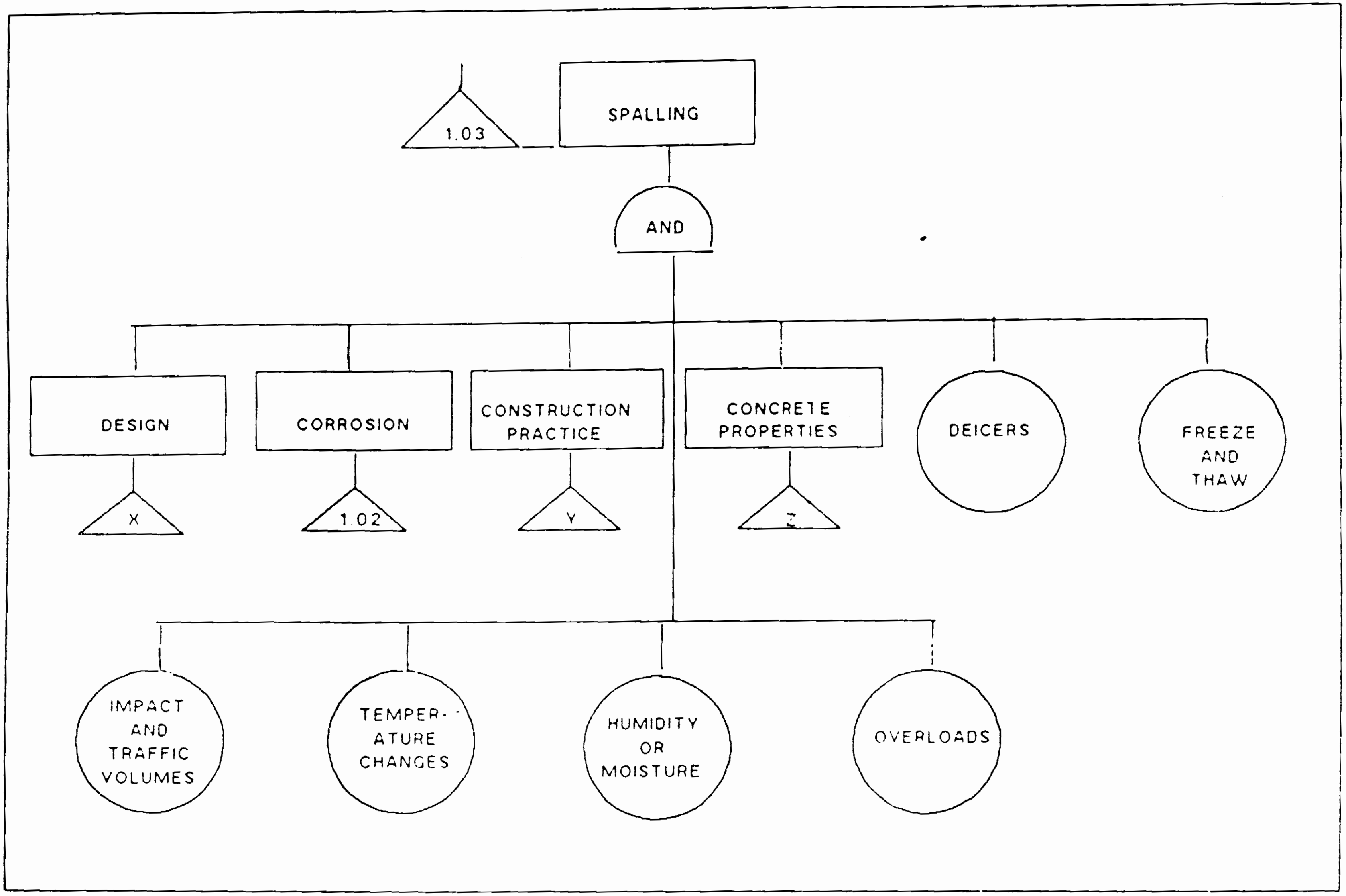


Figure 20. FTA, Spalling Defect and Factors.

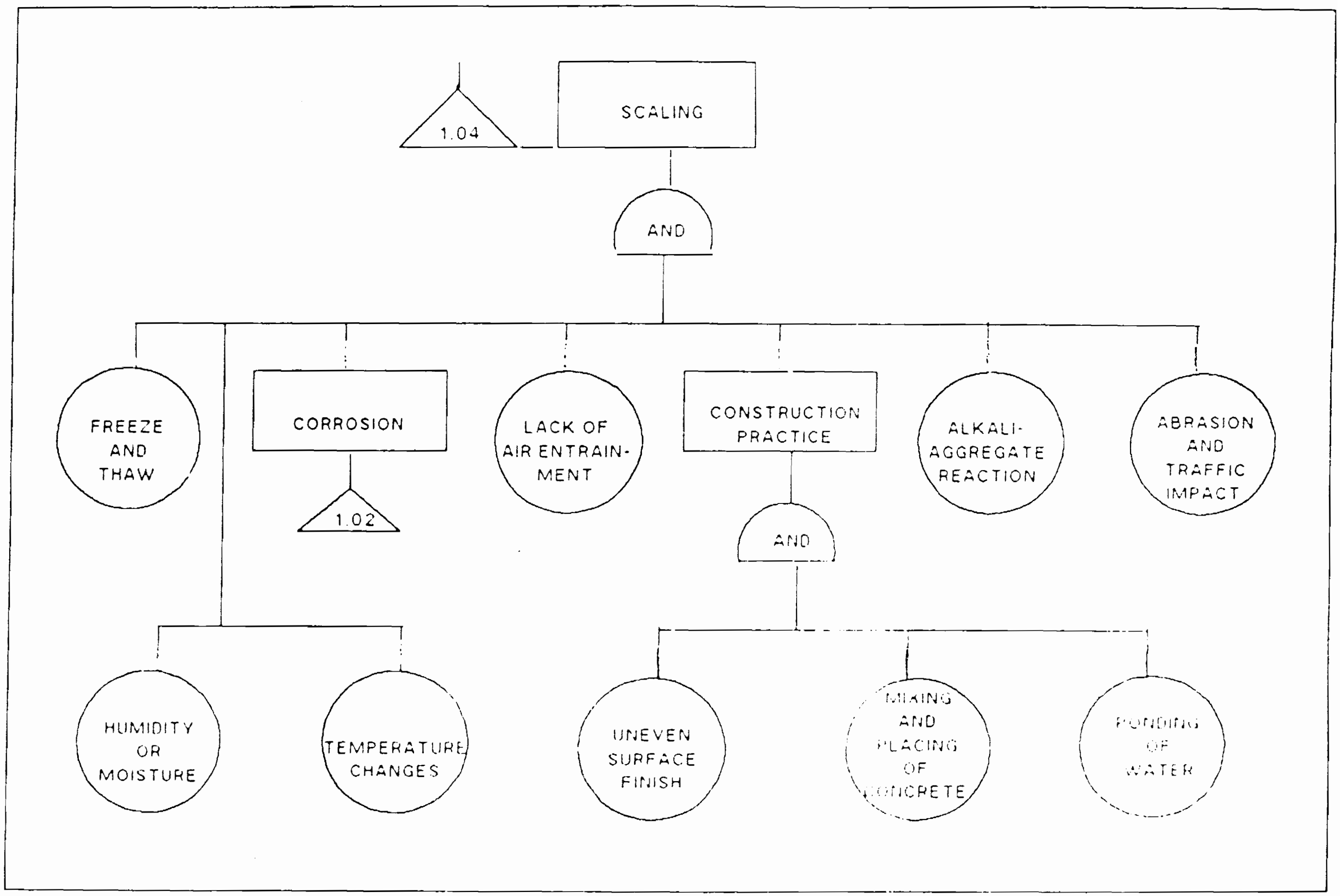


Figure 21. FTA, Scaling Defect and Factors.

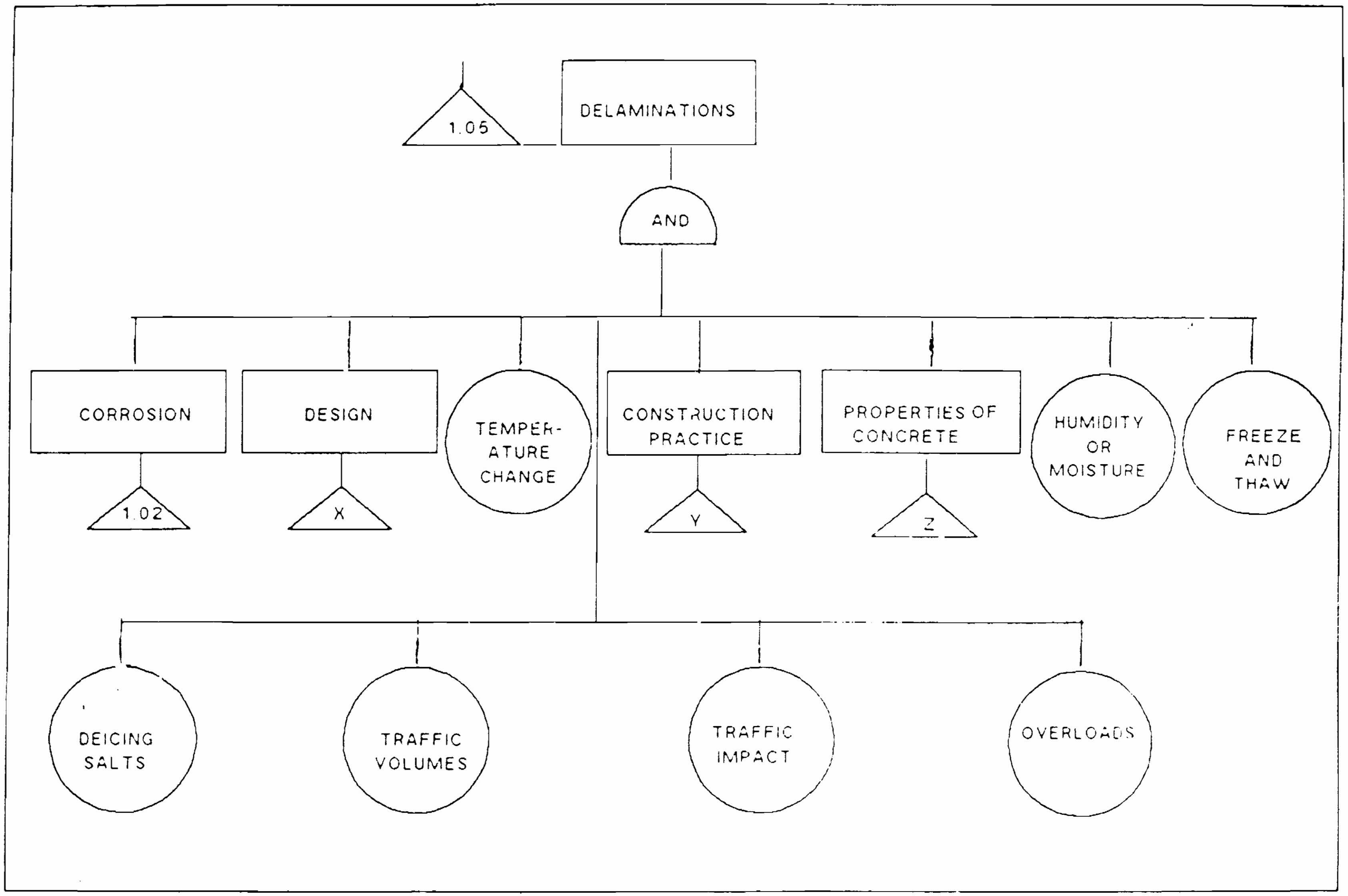


Figure 22. FTA, Delamination Defect and Factors.

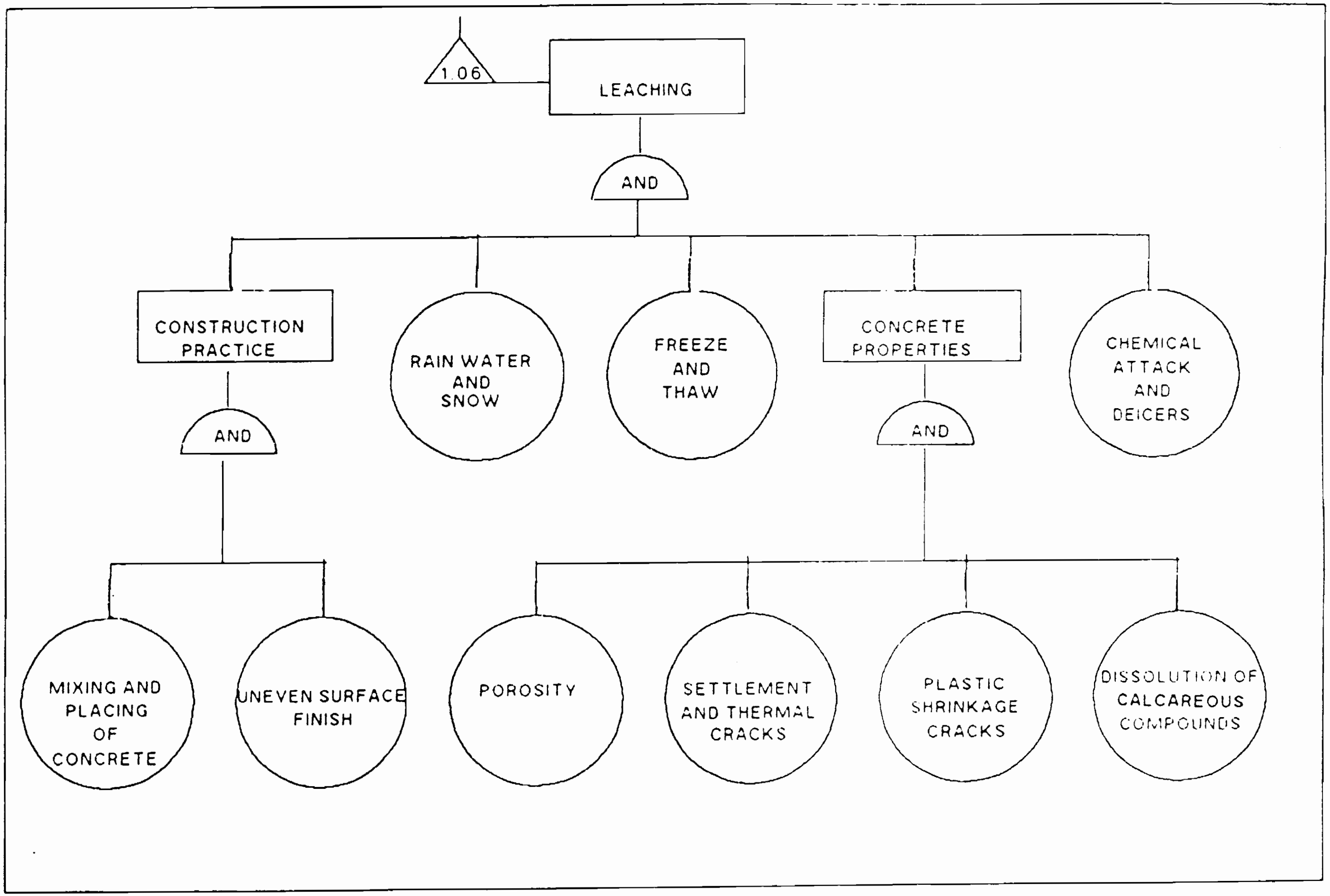


Figure 23. FTA, Leaching Defect and Factors.

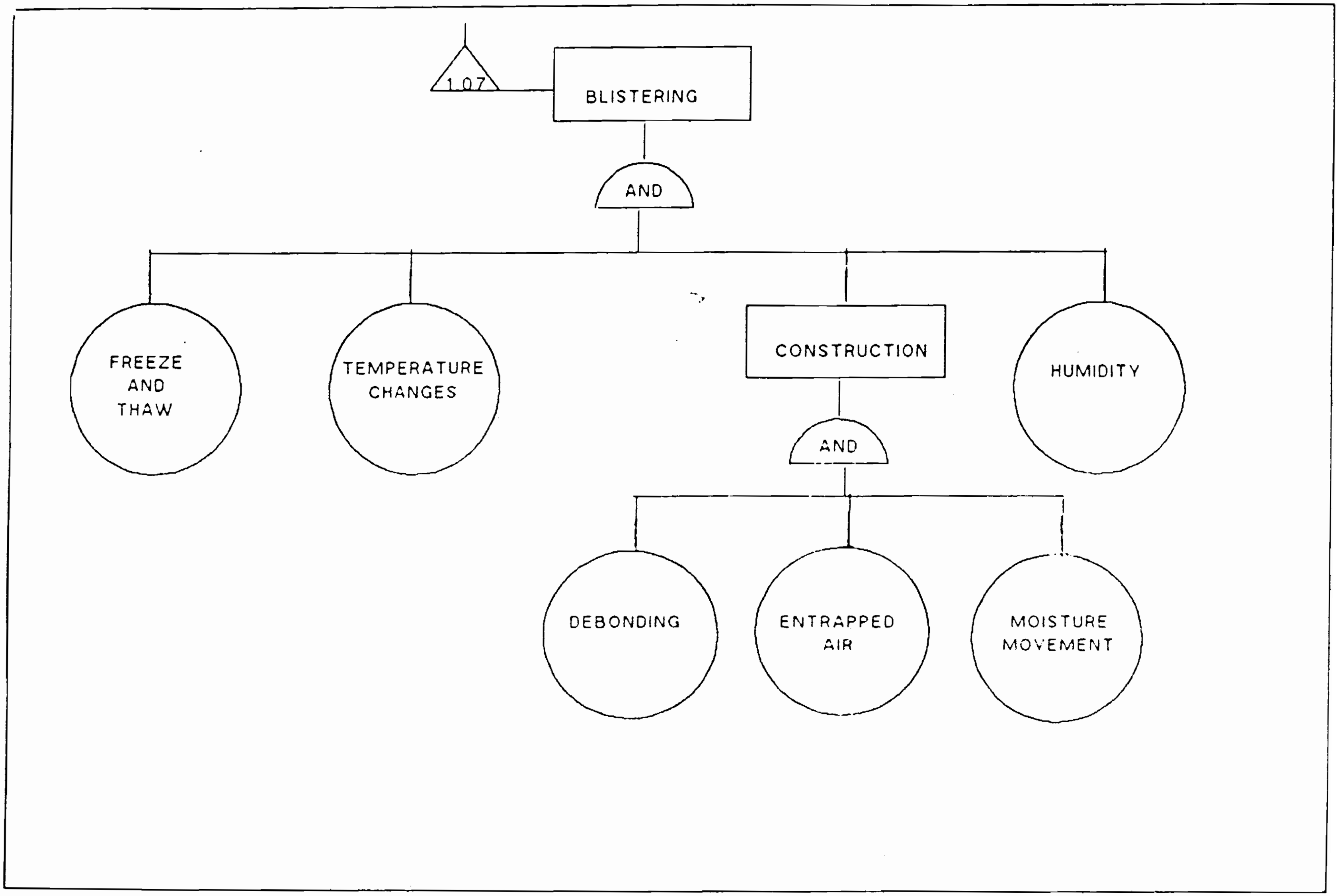


Figure 24. FTA, Blistering and Factors.: Of importance only for decks with water proofing. Not of significance in deck condition evaluation.

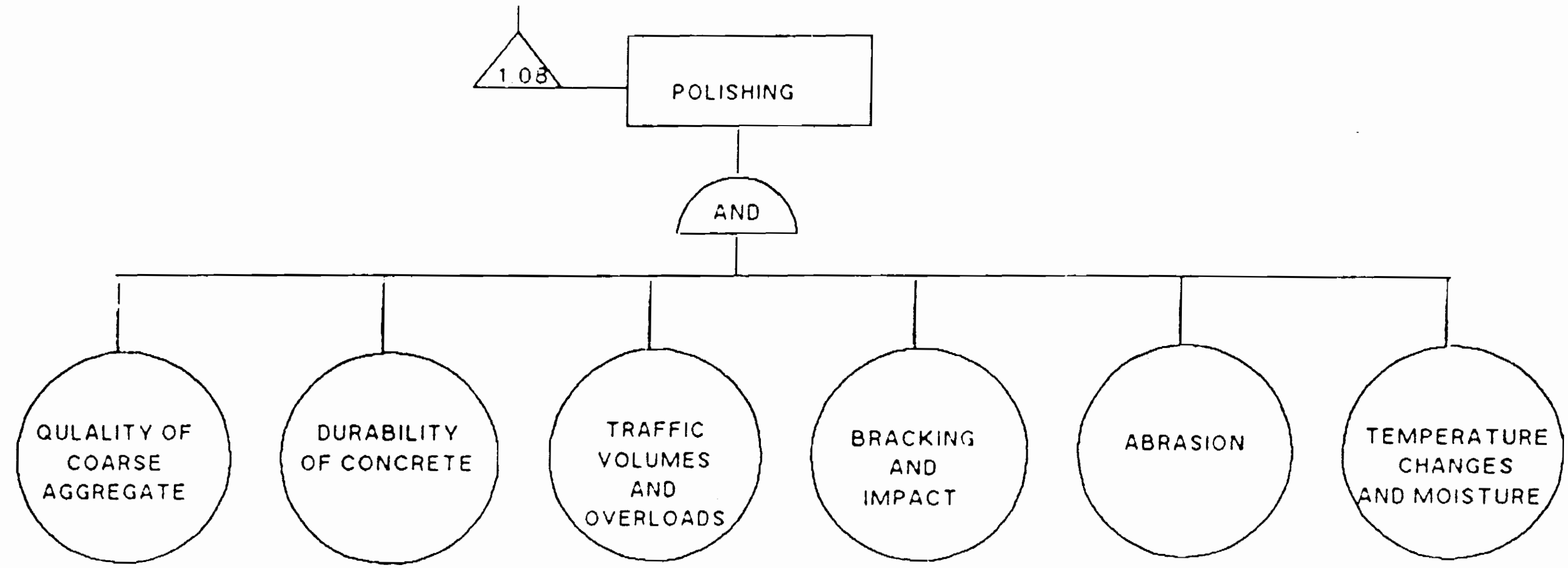


Figure 25. FTA, Polishing and Factors.

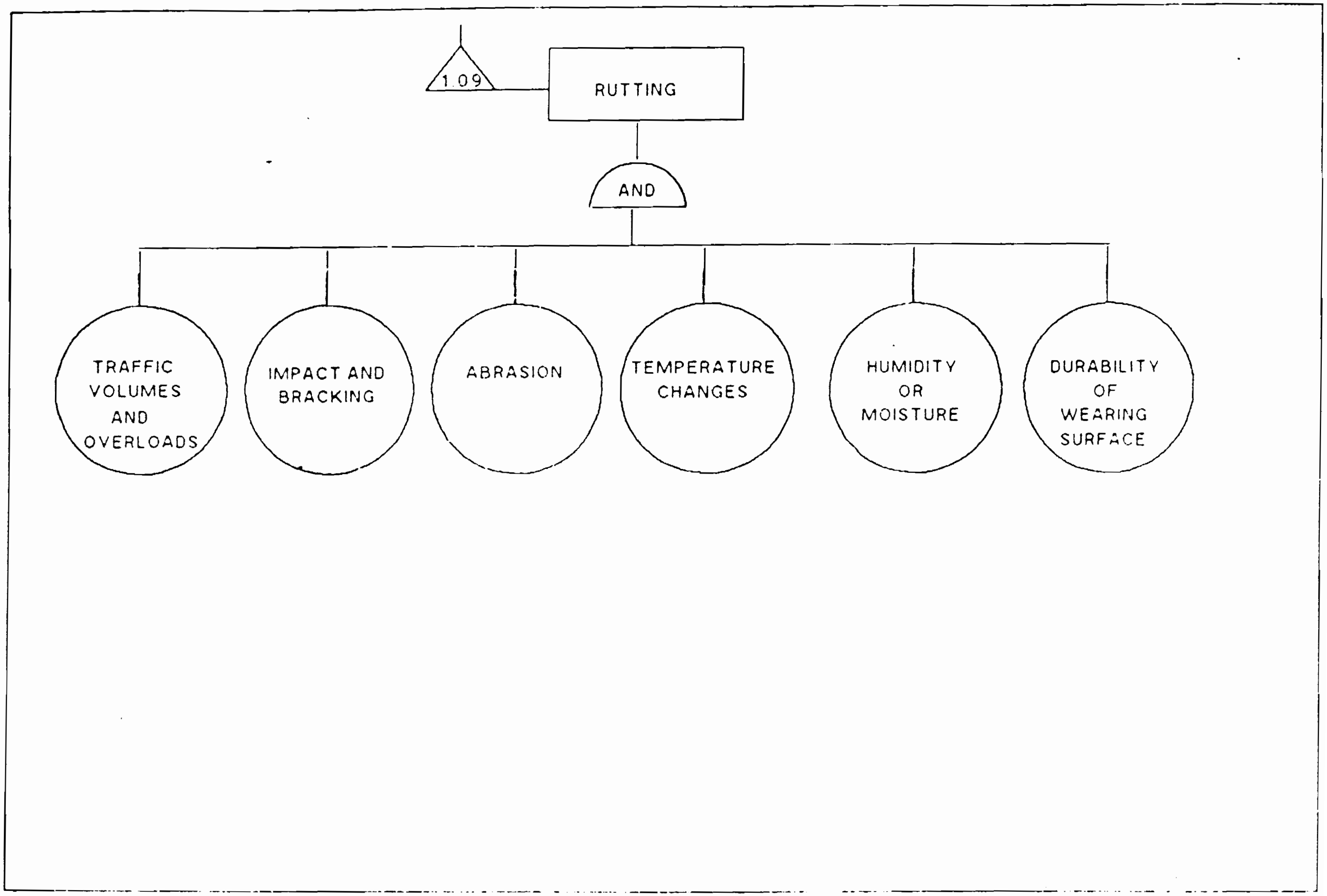


Figure 26. FTA, Rutting and Factors.

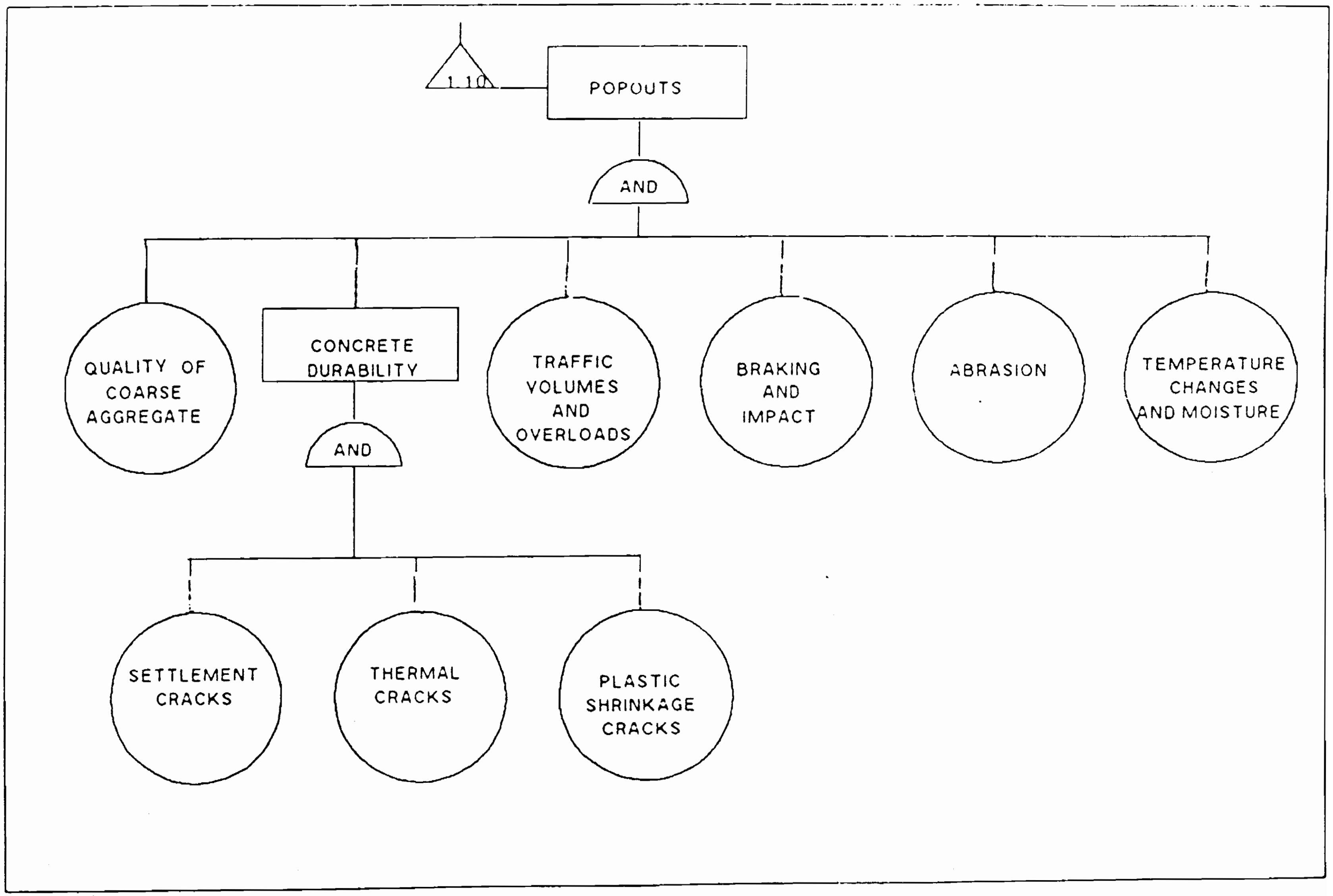


Figure 27. FTA, Popouts and contributing Factors.

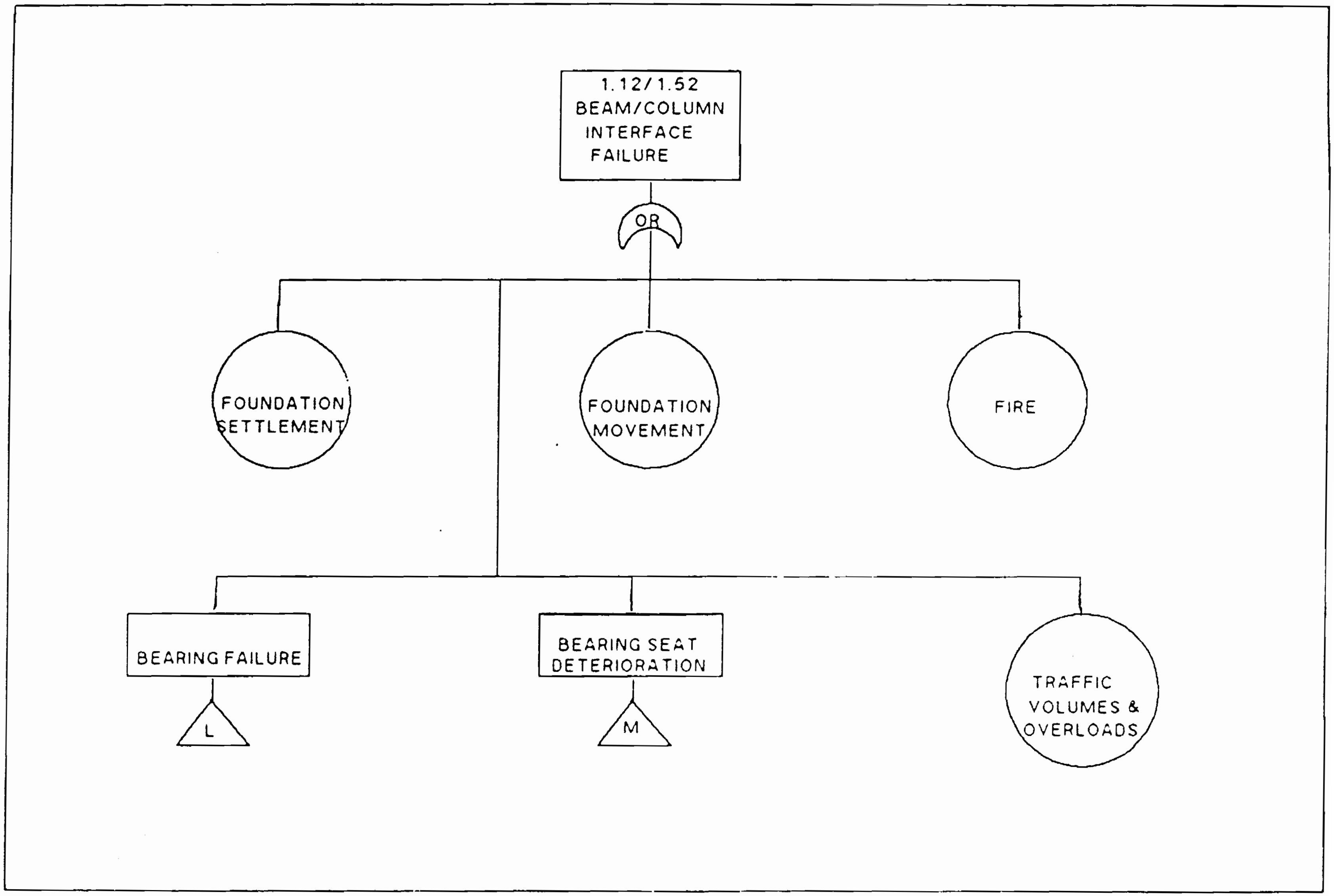


Figure 28. FTA, Beam/Column Interface.: Is part of the superstructure and is of significance in Superstructure Condition Rating than the Deck Rating.

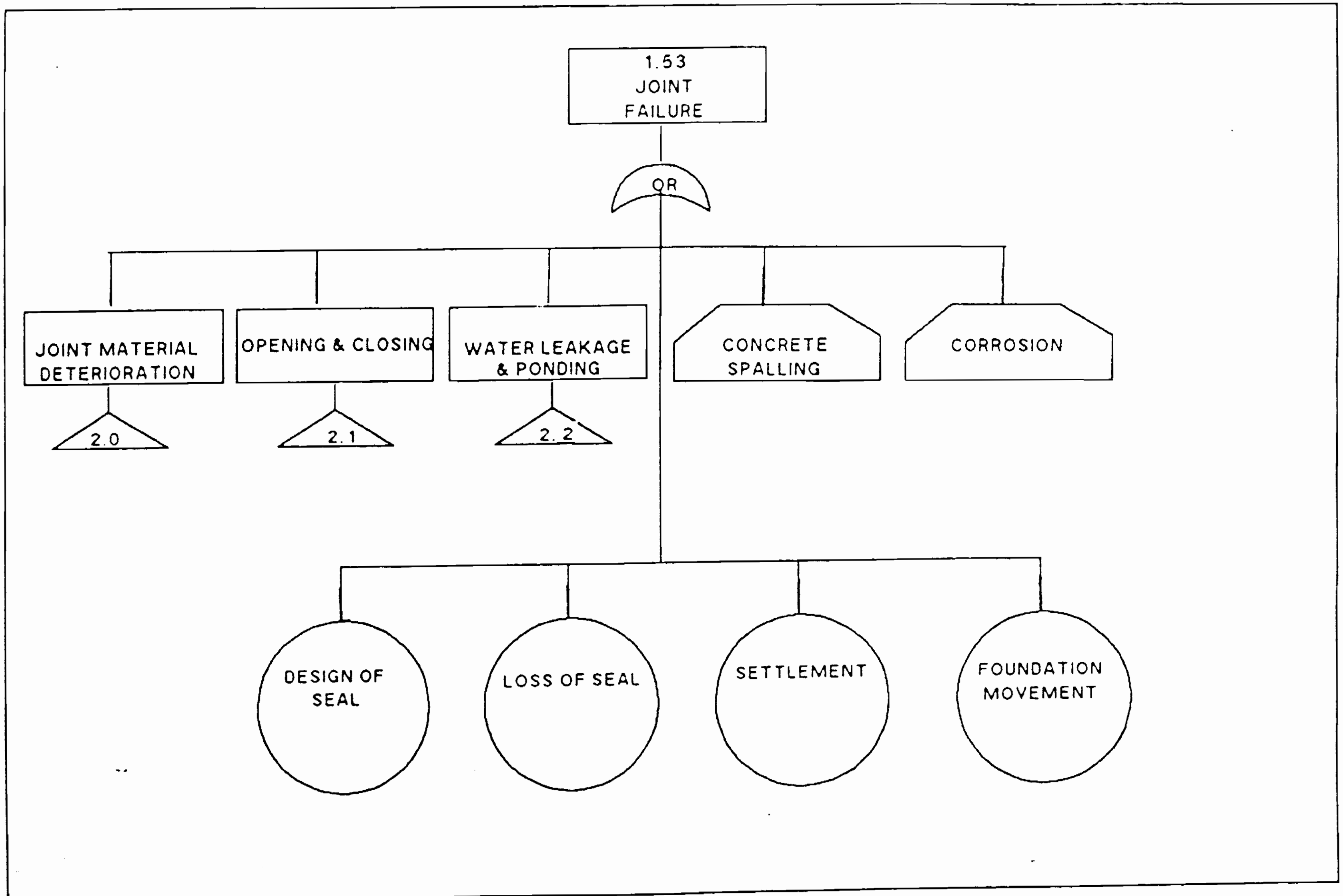


Figure 29. FTA, Joint Failure and Defects.: Expansion joints are a part of the deck and evaluated along with the slab to establish deck condition rating.

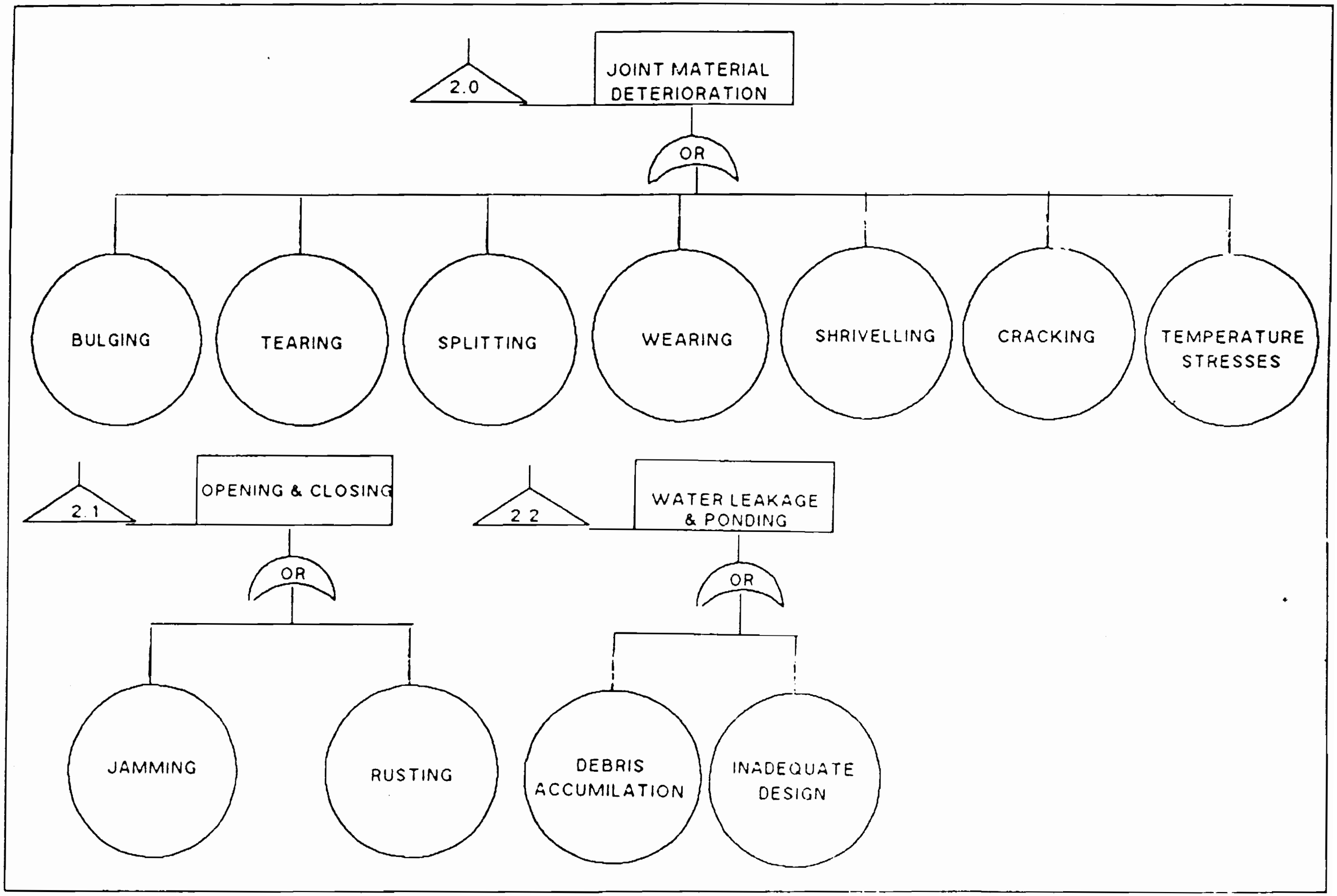


Figure 30. FTA, Joint Material Deterioration and other Defects: Further analyzed to isolate the factors contributing to these defects.

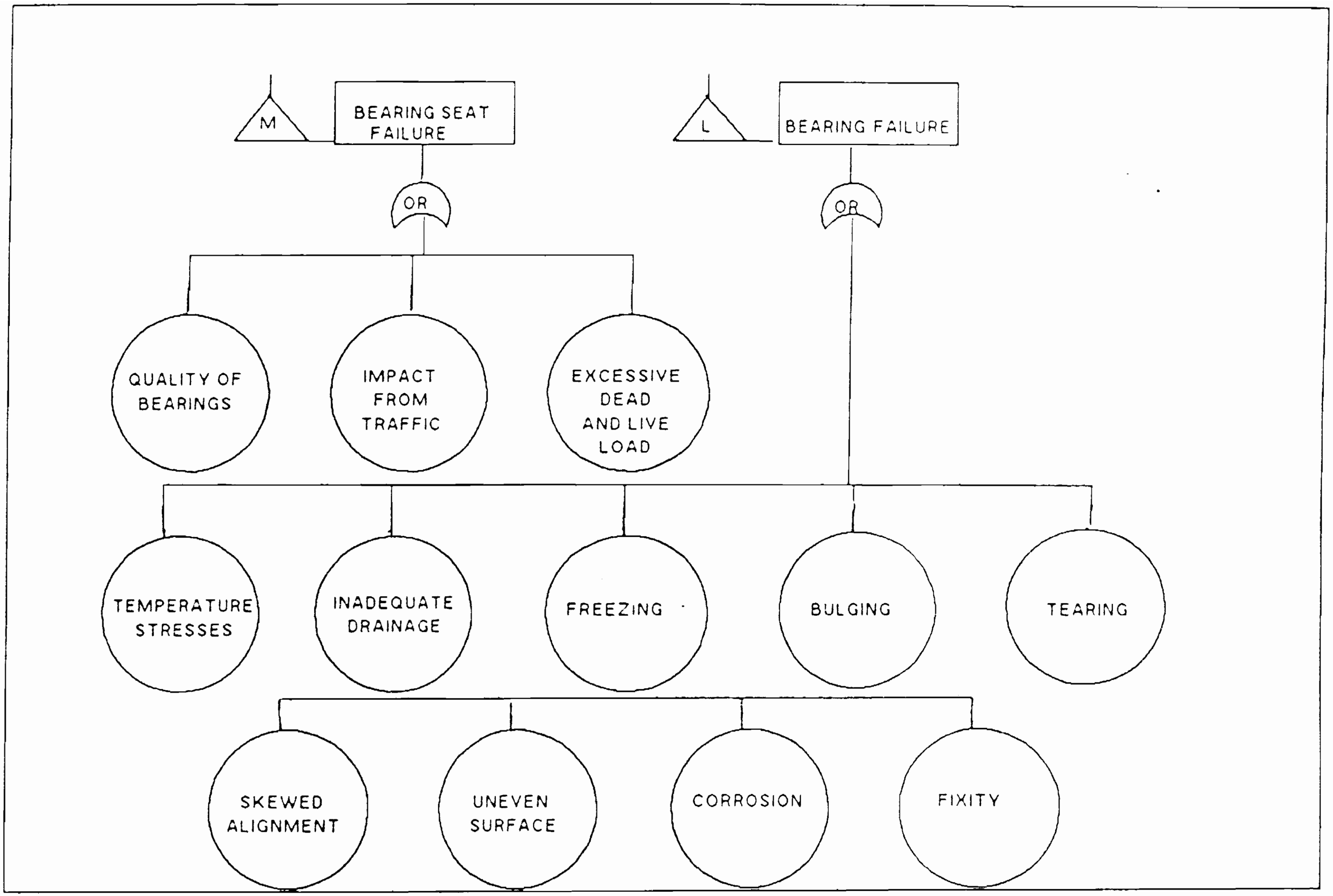


Figure 31. FTA, Bearing Failure and Defects: Bearing failure defects are of significance in Superstructure Condition rating only.

3.2.3. *Special Tables - A*

Tables 5 to 13, pages 63 to 71 : The Special Tables are designed [4][5][6][7][8][9][10][11][13][15][16], to gather substantial information about the severity, extent, appearance/area affected, general location and the critical location of the various defects causing deterioration. The defects are once again prioritized based on significance. The information is made available in a cognitive fashion so that the information is most suitable for the decision tree.

Table 5. Special Tables. Classification of cracking defects based on extent, severity and other characteristics.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	EXTENT	SEVERITY	AREA AFFECTED	APPEARANCE
A) SURFACE AND SUBSURFACE DEFECTS						
1. CRACKING: -Diagonal	• Deck Slabs • Approach Slabs • Vertical Support Members	› Underside of Deck Slabs near Supports › Underside of Beams near Supports › Upperside of Beams continuous over Girder Support › At or near the Bearing Pads and Column caps	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NA	HAIRLINE - < 0.1 mm visible,shallow NARROW - 0.1-0.3, clearly visible, with no spalls MEDIUM - 0.3-0.7, clearly visible, deep, slight spalls WIDE - > 0.7mm, clearly visible, very deep, extensive spalls
-Vertical	• Vertical elements like Columns, Piers Wingwalls & Bents	› Tension zones	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NA	HAIRLINE - < 0.1 mm visible,shallow NARROW - 0.1-0.3, clearly visible, with no spalls MEDIUM - 0.3-0.7, clearly visible, deep, slight spalls WIDE - > 0.7mm, clearly visible, very deep, extensive spalls

Table 6. Special Tables. Classification of cracking defects continued.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	EXTENT	SEVERITY	AREA AFFECTED	APPEARANCE
-Transverse & Horizontal	• Deck Slabs • Sidewalks • Approaches • Curbs • Floor Beams • Pier & Bent Caps	› Midspan of Decks & Beams › Tension side of Intermediate Supports › Approach Slab › Sidewalks & Curb Supports	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NA	HAIRLINE - < 0.1 mm visible,shallow NARROW - 0.1-0.3, clearly visible, with no spalls MEDIUM - 0.3-0.7, clearly visible, deep, slight spalls WIDE - > 0.7mm, clearly visible, very deep, extensive spalls
-Longitudinal	• Deck Slab over longitudinal support members • Approach Slabs	› Tension zones of Deck and Approach Slabs	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NA	HAIRLINE - < 0.1 mm visible,shallow NARROW - 0.1-0.3, clearly visible, with no spalls MEDIUM - 0.3-0.7, clearly visible, deep, slight spalls WIDE - > 0.7mm, clearly visible, very deep, extensive spalls

Table 7. Special Tables: Map and D - Crack Characteristics.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	EXTENT	SEVERITY	AREA AFFECTED	APPEARANCE
-Map or Pattern	* Deck Slabs * Approach Slabs * Vertical Support Members * Abutment Walls	› Both sides of the Deck Slab › Above Wearing Coarse › Surface of Horizontal elements	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NA	HAIRLINE - ‹ 0.1 mm visible,shallow NARROW - 0.1-0.3, clearly visible, with no spalls MEDIUM - 0.3-0.7, clearly visible, deep, slight spalls WIDE - › 0.7mm, clearly visible, very deep, extensive spalls
-D cracks	* Deck Joints * Construction Joints * Approaches	› Paralleling Construction joints › Cracks & Curving across Slab corners	1. FEW 2. INTERMITTENT 3. EXTENSIVE 3. FREQUENT	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NA	1-10mm 10-20mm 20-25mm › 25 mm in width with spalls & faults

Table 8. Special Tables: Delaminations and Spalling.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	EXTENT	SEVERITY	AREA AFFECTED	APPEARANCE
2. DELAMINATIONS	• Deck Slabs • Tees • Approach Slabs • Vertical supports • Horizontal supports	• At Reinforcement level	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NONE < 2.0 % 2.0 - 5.0 % > 5.0 %	NA
3. SPALLING	• Bent Caps • Construction joints • Edges of horizontal supports • Splash zone of vertical members	• On exposed surfaces	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NONE < 2.0 % OR < 1" deep OR approx 6" in Diameter 2.0 - 5.0 % OR > 1" deep AND > 6" in Diameter > 5.0 % OR Hollow sound due to fracture plane underneath	NA

Table 9. Special Tables: Popouts and Scaling.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	EXTENT	SEVERITY	AREA AFFECTED / APPEARANCE
4. POPOUTS	* Anywhere in concrete	NA	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	NOTICEABLE, < 10 cavities/mt sq. OPEN TEXTURE, 10 - 25 cavities over coares aggregate/mt sq. POCK MARKED, in closely spaced shallow patches with size between 0.5 and 1.5" RAVELLED, size > 2.5"
5. SCALING	* Horizontal surfaces and water collecting points	NA	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	< 0.25," exposing coarse aggregate 0.25 - 0.50" in size, loss of mortar and coarse aggregate 0.50 - 1.00" in size, coarse aggregate stand out > 1.00" in size, extensive loss of coarse aggregate and mortar

Table 10. Special Tables: Leaching, Rutting and Polishing.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	EXTENT	SEVERITY	AREA AFFECTED / APPEARANCE
6. EFFLORESCENCE OR LEACHING	• Underside of Decks, Floor beams, Abutment walls and Column caps	NA	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	Barely noticeable Infrequent small patches Small to medium patches, frequent Extensive, all sizes
7. CRAZING	• Deck Slab • Approach slab • Vertical & Horizontal supports	NA	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	Barely noticeable during drying after rain, over the entire area Noticeable, at all areas at all time Well pronounced in scattered areas Well pronounced over entire area
8. RUTTING	• Deck & Approach slabs	NA	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	< 10 mm deep 11 - 15 mm deep 16 - 20 mm deep > 21 mm deep
9. POLISHING	• Deck & Approach slabs	NA	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	Noticeable Distinctive dull finish Glossy mirror finished surface Highly polished

Table 11. Special Tables: Corrosion and other defects.

DEFECTS CAUSING DETERIORATION	GENERAL LOCATION	CRITICAL LOCATION	ELECTRICAL POTENTIAL (VOLTS)	CHLORIDE CONTENT (#/CY)
10. CORROSION	• Anywhere reinforcement is used in concrete	NA	1. NONE 2. NONE > 0.35 3. 45 % of AREA < 0.35	1. NONE 2. NONE > 1.0 3. NONE > 2.0
OTHER DEFECTS	GENERAL LOCATION	EXTENT	SEVERITY	APPEARANCE
B) STRUCTURAL DEFECTS 1. FAULTING	• Construction joints in Deck • Cracks	1. FEW 2. INTERMITTENT 3. FREQUENT 4. EXTENSIVE	1. NOT SEVERE 2. MODERATE 3. SEVERE 4. VERY SEVERE	< 3 mm displacement 3 - 6 mm displacement 7 - 15 mm > 15 mm displacement
2. COLLISION	• Deck • Curbs • Sidewalks • Railings • Columns	Measure loss of section / displacement / movement or cracked section		

Table 12. Special Tables: Joint defects and their characteristics.

DEFECTS CAUSING DETERIORATION	EXTENT	SEVERITY	APPEARANCE
1. MATERIAL DETERIORATION - BULGING - TEARING - SPLITTING - WEARING - SHRIVELLING - CRACKING	1. NOT EXTENSIVE 2. EXTENSIVE	1. NOT SEVERE 2. SEVERE	NA
2. OPENING & CLOSING - JAMMING - RUSTING - ALIGNMENT	1. NOT EXTENSIVE 2. EXTENSIVE	1. NOT SEVERE 2. SEVERE	NA
3. WATER LEAKAGE & PONDING	1. NOT EXTENSIVE 2. EXTENSIVE	1. NOT SEVERE 2. SEVERE	NA

Table 13. Special Tables, Deterioration Indicators and Significance Values.

DEFECTS CAUSING DETERIORATION	SIGNIFICANCE	QUALITATIVE VALUE
DECK SLAB:		
1. CRACKING	VERY	2
2. CORROSION	VERY	2
3. SPALLING	VERY	2
4. SCALING	VERY	2
5. DELAMINATIONS	VERY	2
6. LEACHING	VERY	2
7. POPOUTS	SIGNIFICANT	1
8. RUTTING	SIGNIFICANT	1
9. CRAZING	NOT SIGNIFICANT	0
10. POLISHING	SIGNIFICANT	1
11. FAULTING	VERY	2
12. COLLISION DAMAGE	SIGNIFICANT	1
JOINT:		
1. MATERIAL DETERIORATION	VERY	2
2. OPENING & CLOSING	VERY	2
3. WATER LEAKAGE	SIGNIFICANT	1

3.2.4 *Special Tables - B*

This table, Table 14, page 86 relates the condition index to the probable range of failure.

3.2.5 *Decision Tree*

In this study the deck is considered to be made up of the regular concrete deck slab and joints and both are evaluated under the substructure category.

3.2.5.1 Assumptions: Figure 31, page 73 : No reference ,to the generally found flow chart graphical representations are made. Only rectangles and descriptive questions in the form of yes and no are used to seek solutions. For each defect which is positive, the extent, severity and significance are evaluated quantitatively The extent and severity are added and the sum is multiplied by the significance to get the total numerical value. This is repeated for all the listed and occurring defects and the cumulative total is then related to the C/I range. C/I range is from 9 to 0 which is the standard in almost all the states. It is divided in to 4 categories as shown in Table 14, page 82

The Recording and Coding Guide, Figure 8, page 26 has a special table where some of the many probable defects which cause deterioration are identified and their extent and severity are evaluated to arrive at a thumb rule to rate the deck condition due to deterioration. But the information on the indicators is not exhaustive enough and there are only a few of them chosen to rate the deck condition. A well organized and complete table which can serve the purpose is required. In this study careful attention is given to the other forms of deterioration and a comprehensive new table is prepared by comprehending the information given in the Special Tables Module and quantifying it in the Decision Tree.

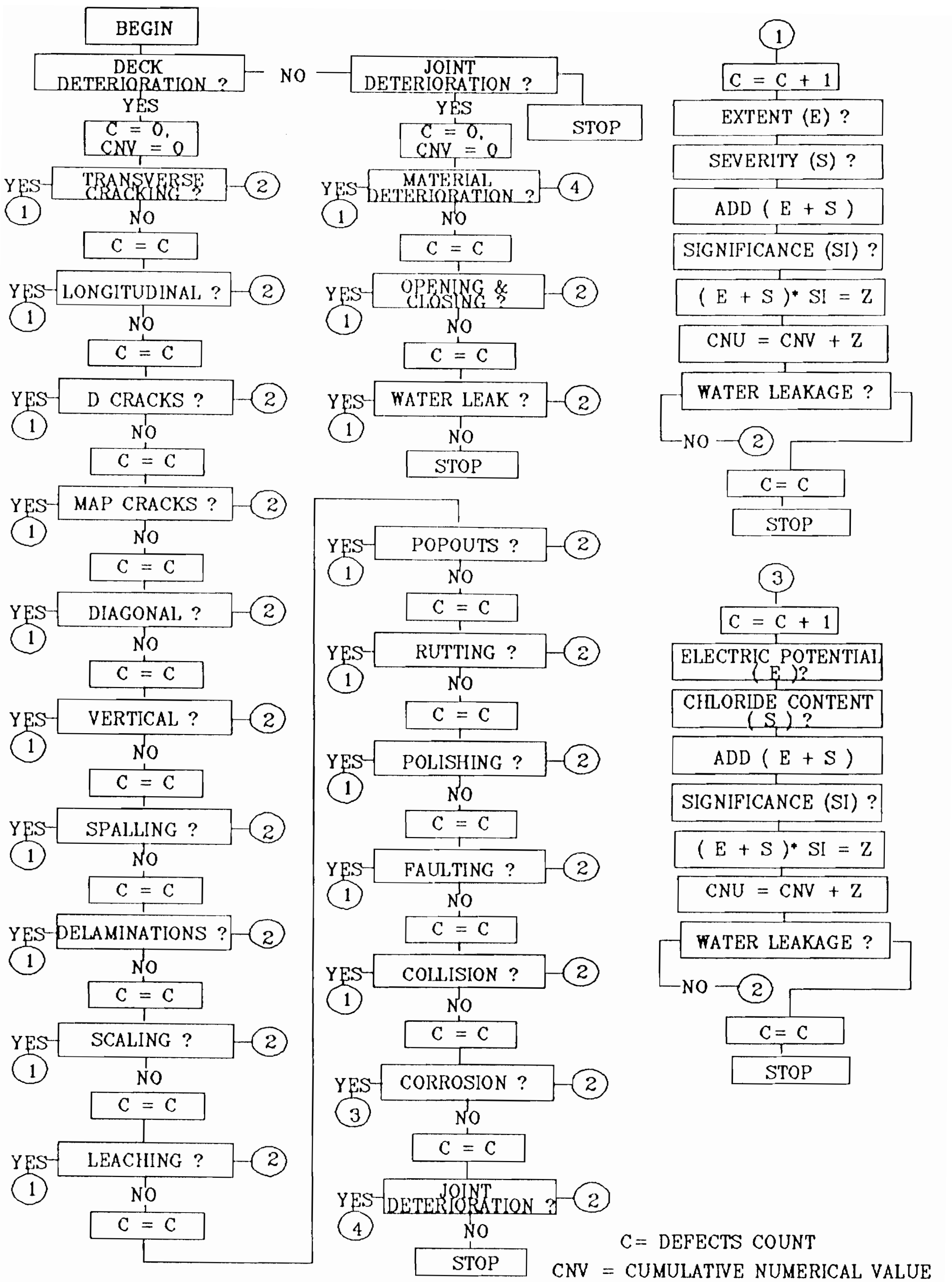


Fig. 31. Deterioration Decision Tree

3.2.6 C/I v/s Service Graph or Deterioration Module

There many methods by which the deterioration of bridge decks can be ascertained. Analysis of site condition data by statistical methods such as, regression analysis is the most common. Determining material behavior under simulated conditions in the laboratory and recording the results is another.

The recorded deck condition data for one particular bridge in Northern Indiana [22], for which inspection results for well over 60 years has been obtained was used to plot the condition index values v/s service life to generate a graph as shown in Figure 32, page 75. This form of curve sloping is typical for concrete deterioration.

Research results show that almost all bridges follow the same pattern of deterioration more or less. Analyzing a sample set of data by either any of the statistical method generates a curve which is straight and which does not necessarily represent the deterioration process occurring naturally. Discrete Markov Chains [2][22][23], which is an stochastic analytical technique, sometimes also recognized as a systems engineering technique is one tool which is suitable for this work and which has found large application in industrial engineering is used to predict the future condition of the component under investigation, given the present condition, assuming that the same factors causing deterioration exist in the future but whose values vary in a nonlinear fashion.

Figure 33, page 79 is the graph plotted using Markov Chains [22]

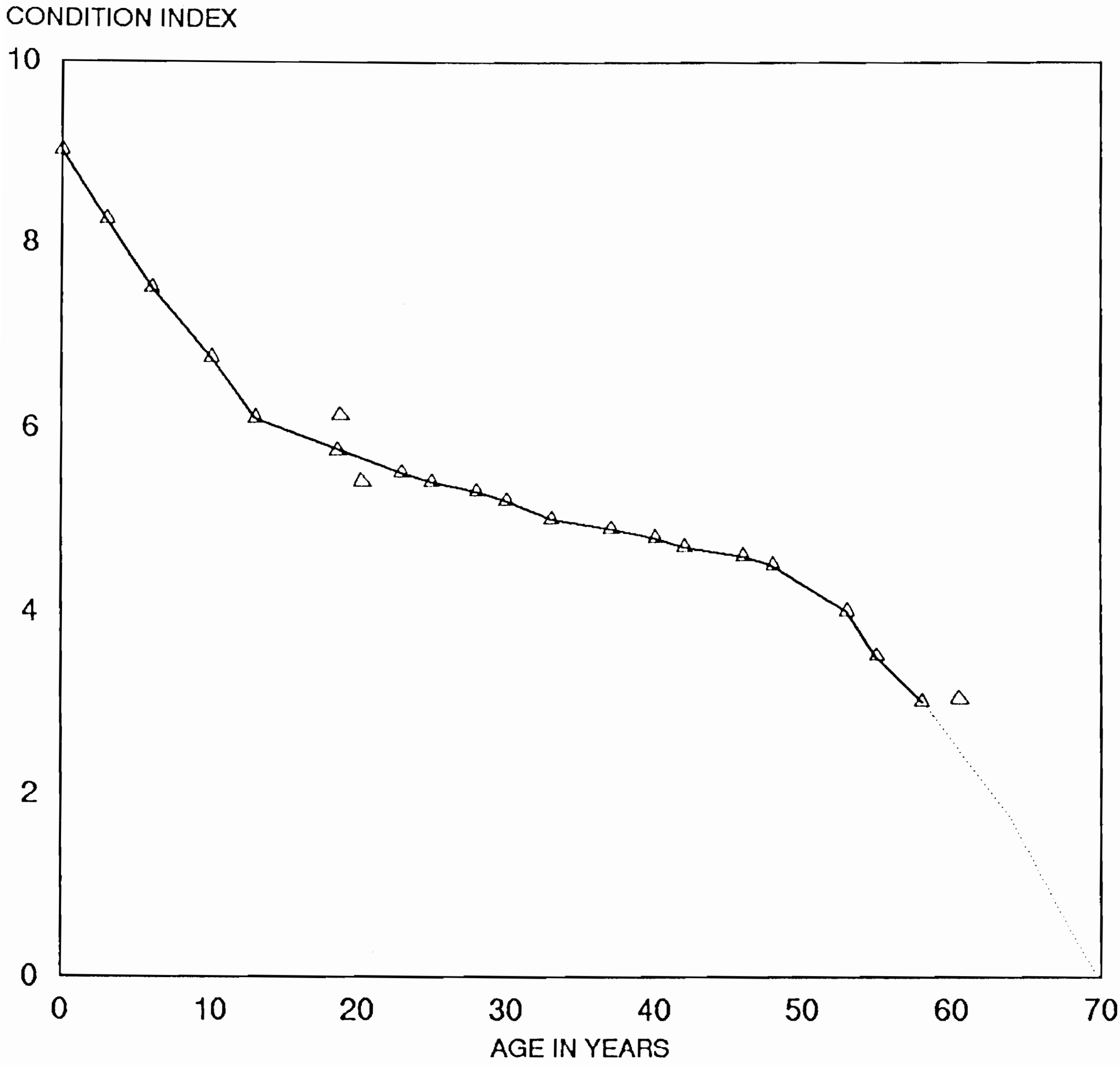


Figure 32. Condition Index V/S Service Life Graph.: Source, Reference 26.

3.2.6.1 Assumptions

1. Deterioration is considered continuous and the various defects like corrosion, leaching, spalling etc., influencing the rate of deterioration are considered to vary in a nonlinear fashion throughout the estimated service life.

2. There are no priori probabilities with which the C/I values can be predicted at any given time.

3. The design life of the deck is divided into zones or periods each of width six years, during which deterioration is assumed constant.

4. The deterioration rate for each period is different and independent of the other and is different in value.

5. The condition indices are from 9 to 0 and the deck can have any value at any given year. When transition is to be made from one period to another, the condition index values changes [decreases] and they have to be predicted with a fair degree of confidence since it is unknown.

6. When the deck is constructed it is assumed to be in excellent condition and in the 0th year it has a rating of 9. This can be said with 100 percent confidence or the probability that the condition index is 9 at the 0th year is 100 percent.

7. At the beginning of the 1st year the condition does not remain the same as in the 0th year. Either it remains the same or decrease in value. And this value has to be found.

8. The State Vector is a set of numerical values between 1 and 0 representing the probability value related to the condition index. For example the state vector for the 0th year is *[1,0,0,0,0,0,0,0,0,0,]* . (That is the condition index in the 0th year is 9 and it can be represented with 100 percent confidence and the state vector corresponding to 9 is 1 meaning, 100

percent probability. It has been understood that the condition index is rarely below 3. The reason being the bridge engineers are reluctant to assign a value below 3 because it indicates structural inadequacy requiring replacement. The reluctance to accept this fact and to propose a value equal to or greater than 3 is quite common because, it is believed that some sort of repair work despite the cost is worthier than declaring the bridge to be unsuitable. Therefore the condition index values below three are not considered here, and instead, a range from 9 to 3 is considered. When the c/i is 3 then, it is said that the deck is ready for replacement).

9. Therefore, the state vector has a set of 7 values instead of 10 and the state vector for the 0th year can now be written as *[1,0,0,0,0,0,0]*.

If $p1$ represent the probability that the condition index is 9 at the beginning of the 1st year and $q1$ is the probability of being any value other than 9; similarly if $p2,p3,p4 ...p6$, are the probabilities that the condition indices are 8,7,6...3 in the 2nd,3rd, year and $q1,q2,q3...q5$ representing any value other than $p1,p2,p3...p5$. Then for the 1st period of 6 years we have a matrix called the transition matrix which is as follows:

$$\begin{bmatrix} p1 & q1 & 0 & 0 & 0 & 0 \\ 0 & p2 & q2 & 0 & 0 & 0 \\ 0 & 0 & p3 & q3 & 0 & 0 \\ 0 & 0 & 0 & p4 & q4 & 0 \\ 0 & 0 & 0 & 0 & p5 & q5 \\ 0 & 0 & 0 & 0 & 0 & p6 \end{bmatrix}$$

here $p6 = 1$

To find $p1, q1$ and the remaining values somepriori condition values are required. A condition rating data set for a bridge deck in Northern Indiana was obtained and a polynomial regression analysis was performed to develop an equation with service life as the only independent variable. The equation is given below:

$$A = 9.0 - 0.30266t^1 + 0.00895t^2 - 0.00009t^3$$

In the equation by substituting the value of time in years gives the condition index for that particular year. Next, the Fletcher-Powell Algorithm, [23], which is a nonlinear optimization program is used to develop the transition matrix probabilities. The equation is as follows:

Minimize $X = \sum_{1}^{N} |A - B|$ Subject to $0 < pi < 1$, i = 1, 2, .., 6

where $A = 9.0 - 0.30266t^1 + 0.00895t^2 - 0.00009t^3$, the average of condition ratings at time t, [obtained by polynomial regression of the c/i's with age as the independent variable].

$B = E(t,P)$, the estimated value of condition rating by Markov Chains at time t

Here $N = 6$, the number of years in one age group;

and $P = [p1, p2, p3, p4, p5, p6]$, a vector of length 6.

There is another property of the state vector;

If $v0$ is the state vector at time 0, $v0 = [1, 0, 0, 0, 0, 0]$. And if X is the transition matrix for at time 0;

$$v0 = [X]^0 * v0$$

At 1 year, $v1 = [X]^1 * v0$ and at 6 years, $v6 = [X]^6 * v0$

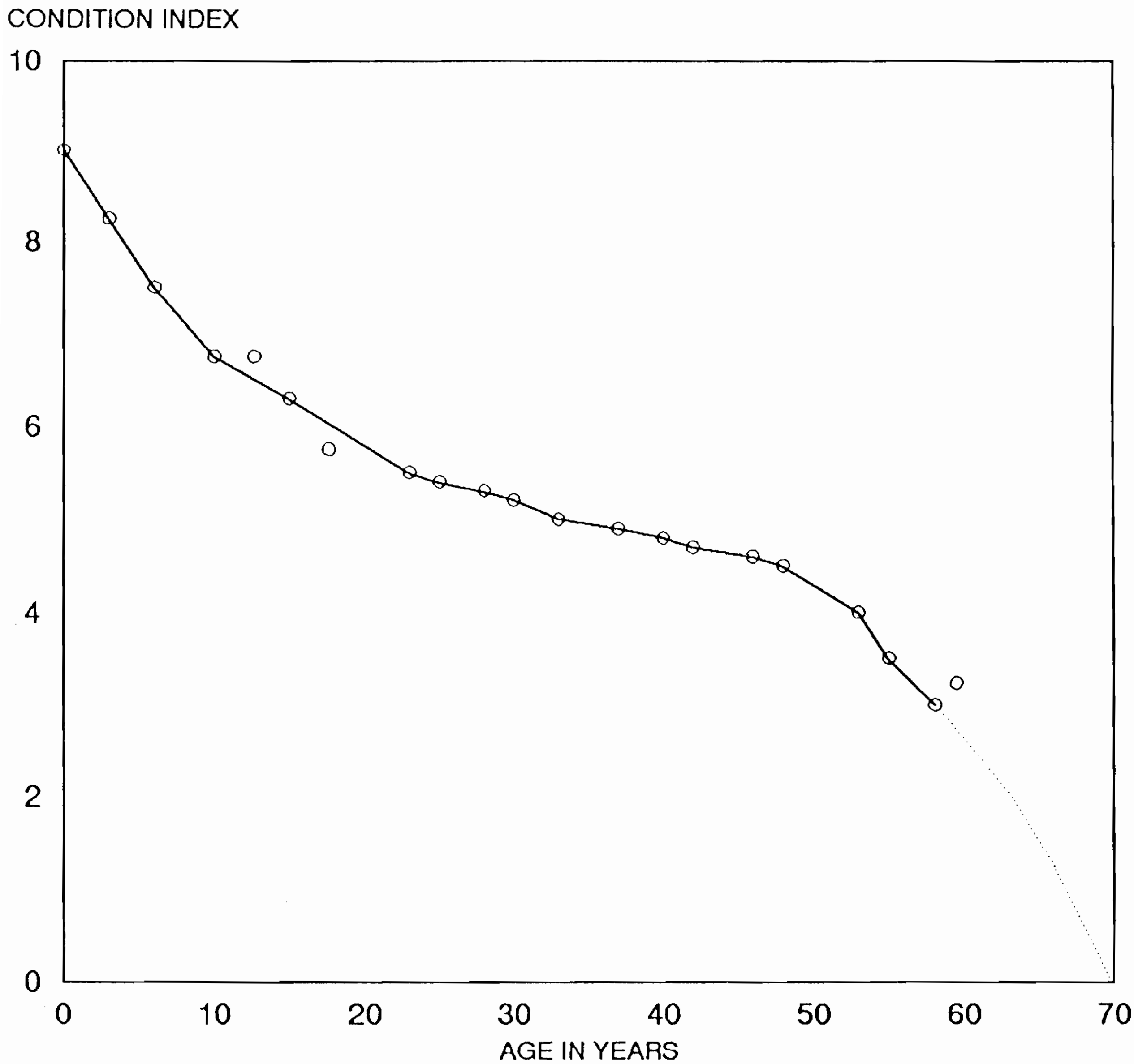


Figure 33. Predicted Condition Index V/S Service Life Graph.: Predicted by Using Markov Chains.

Similarly the state vectors for all the years can be obtained. And any of the $p(n)$ value greater than or equal to 0.5 in the equation indicate that particular outcome has the highest probability value attached to it and the C/I value represented by it is then plotted on the graph to get the deterioration curve. In this way the condition of the bridge deck in any future year given the condition of the deck in the first year is obtained by employing Markov Chains.

3.2.6.2 Reliability Range

Once the C/I value is known then the related reliability, probable range and the associated service life range can be acertained by producing the lines bordering the C/I ranges on to the graph, Figure 34, page 81

Vertical lines are then drawn from the points of inflection on the graph on to the abscissa to get the range of service life associated with each C/I range. The area below the graph indicates the reliability or serviceability of the bridge deck which has 100 percent probability associated with it and the area above the graph indicates 100 percent probability associated with failure. Reliability connected with service life range and condition index range can be found in Figure 35, page 92 .

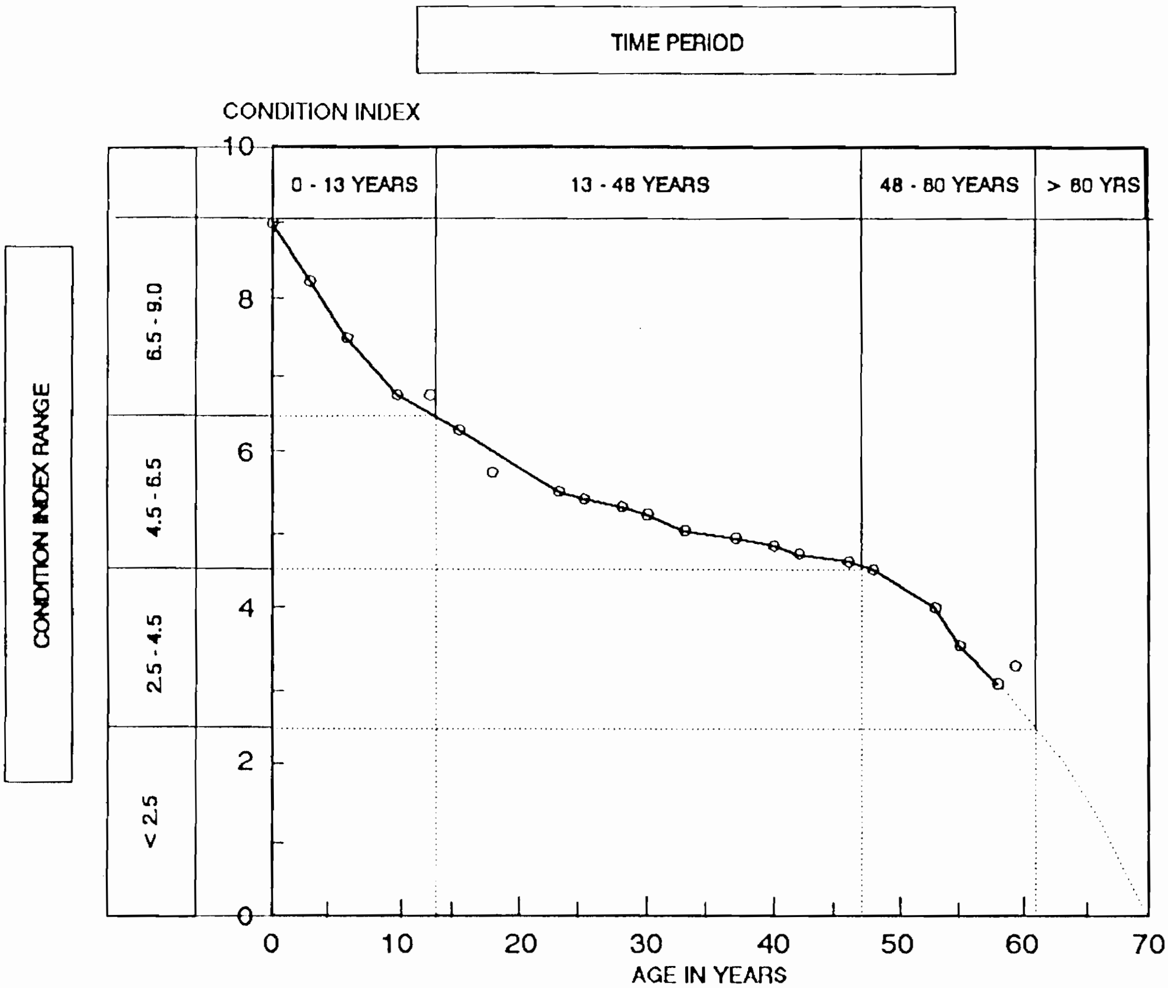


Figure 34 Condition Index Categories and Corresponding Service Life Ranges.: Within each category the deterioration rate is assumed to be constant.

Table 14. Condition Indices and Failure Probability Ranges.

CONDITION INDEX RANGE		DETERIORATION CATEGORY	TIME PERIOD
1	9.0 - 6.5	LIGHT DETERIORATION	< 13 YRS
2	6.5 - 4.5	MEDIUM DETERIORATION	13 - 48 YRS
3	4.5 - 2.5	EXTENSIVE DETERIORATION	48 - 60 YRS
4	< 2.5	STRUCTURALLY INADEQUATE DECK	> 60 YRS

Source: Fig. 35, page 95.

3.2.7 Quantification of Defects and Relating Them to the Condition Indices

Tables 5 to 13, pages 63 to 71 refer to the special tables which has information on the extent, severity and significance of each defect causing deterioration. There are 19 defects listed which include 6 types of cracks found in the reinforced deck and the expansion joints. Even though the list is not exhaustive it is comprehensive and includes all those defects which are commonly appearing and have been discussed in many references. Cracking; all types, delaminations, spalling, leaching, scaling, faulting, joint material deterioration, opening and closing of joints and corrosion are significant indicators of deterioration while popouts, rutting, polishing, collision damage, and water leakage are considered to be of minor significance, **[4][5][8][10][13]**

The first set of defects are assigned a numerical value of 2 and the second set a numerical value of 1 to denote their respective significance Table 13, page 71. All but corrosion defect, joint material deterioration and opening and closing in the first category, have 4 levels each, of extent and severity. Corrosion has 3 levels and the remaining two have 2 levels, Figure 11, page 42.

Similarly in the second category all except opening and closing and water leaking have 4 levels each of extent and severity while the latter have two. As discussed earlier, in the Decision Tree the effect of each combination of extent and severity for each defect will be added and multiplied by the respective significance number to arrive at the final value. This is done as shown below.

For example; Traverse Cracking has extent and severity in four levels

EXTENT	SEVERITY
1 Few	*1* Not Severe
2 Intermittent	*2* Moderate
3 Frequent	*3* Severe
4 Extensive	*4* Very Severe

Adding the values, 6 combinations are possible and they are:

$$\begin{bmatrix} 2 \\ 3 \\ 4 \\ . \\ . \\ 8 \end{bmatrix}$$

Multiplying by the significance value 2 gives:

$$2 \begin{bmatrix} 2 \\ 3 \\ 4 \\ . \\ . \\ 8 \end{bmatrix} = \begin{bmatrix} 4 \\ 6 \\ 8 \\ . \\ . \\ 16 \end{bmatrix}$$

There are 11 such sets for 11 different very significant defects having the same combination, which can be represented conveniently as:

$$11\begin{bmatrix}4\\6\\8\\.\\.\\.\\16\end{bmatrix}$$

Similarly for corrosion defect we have; *1[4, 6, 8...12]*

For popouts, rutting, polishing and collision damage; *4[2, 3, 4....8]*

For opening and closing and material deterioration; *2[4,6,8]* and water leakage; *1[2, 3, 4]*

Each of the above sets can be expanded by multiplying the values inside the brackets by the defects represented by the number outside, by taking one defect at a time and increasing by one after each step.

That is for example: *2[4, 6, 8]* will become,

$$1\begin{bmatrix}4\\6\\8\end{bmatrix} + 2\begin{bmatrix}4\\6\\8\end{bmatrix}$$

After multiplication these values can be represented as a range within common brackets:

$$\begin{bmatrix} 4 & 8 \\ 6 & 12 \\ 8 & 16 \end{bmatrix}$$

Multiplying all sets and arranging them in order we get:

$$11\begin{bmatrix} 4 \\ 6 \\ 8 \\ . \\ . \\ 16 \end{bmatrix} \quad 1\begin{bmatrix} 4 \\ 6 \\ 8 \\ . \\ . \\ 12 \end{bmatrix} \quad 4\begin{bmatrix} 2 \\ 3 \\ 4 \\ . \\ . \\ 8 \end{bmatrix} \quad 2\begin{bmatrix} 4 \\ 6 \\ 8 \end{bmatrix} \quad 1\begin{bmatrix} 2 \\ 3 \\ 4 \end{bmatrix}$$

which is:

$$\begin{bmatrix} 4...44 \\ 6...66 \\ 8...88 \\ . \quad .. \\ 16..176 \end{bmatrix} + \begin{bmatrix} 4 \\ 6 \\ 8 \\ . \\ 12 \end{bmatrix} + \begin{bmatrix} 2..8 \\ 3..12 \\ 4..16 \\ . \quad .. \\ 8..32 \end{bmatrix} + \begin{bmatrix} 4 & 8 \\ 6 & 12 \\ 8 & 16 \end{bmatrix} + \begin{bmatrix} 2 \\ 4 \\ 6 \end{bmatrix}$$

The least possible combination can be:

*Least value of (extent + severity) * Minimum level of significance * Miminum # of defects*

which is: $(1+1)*1*1 = 2$

Similarly the worst possible combination can be:

*Max. value of (extent + severity) * Max. level of significance * Max. # of defects*

which is:

$$(4+4)*2*11 + (3+3)*2*1 + (4+4)*1*4 + (2+2)*2*2 + (2+2)*1*1 = 240$$

Therefore the least possible value is 2 and the maximum value is 240.
The c/i has a range from 9 to 0, but the relationship cannot be simply linear as indicated below with an example.

Now, $(4+4)*2*11 = 176$, which is one of the worst combinations of severity and extent for 11 very significant defects. On a linear scale $176 = 6.65$, which belongs to the light deterioration category Table 14, page 85, which is not true.

Therefore an alternate strategy has to be adapted to arrive at a meaningful relationship.

Some assumptions are made for this purpose.

Assumptions:

- Any 6 significant defects at their worst combination will put the rating into the threshold of extensive deterioration.

- Each c/i value has a range of numerical values with upper and lower limits.

- All 12 very significant defects at their worst combination will result in a value which will be the lower limit on c/i 0.

- The maximum cumulative value of all 19 defects at their worst combination will be the upper limit on the c/i 0.

- The least possible value will be the upper limit on c/i 9. And 0 will be the lower limit.

- A difference of 1 is assumed between the upper limit of an c/i and the lower limit of the c/i immediately following the one above.

- Within each deterioration category the relationship between c/i and associated numerical values will be linear.

Now, going by the assumptions, according to the 1st assumption:

$(4+4)*2*6 = 96$, will be the lower limit on the c/i 3.

According to the 2nd assumption, All 12 very significant defects which includes all the 6 cracking defects at their worst combination yields a value,

$(4+4)*2*11 + (3+3)*2*1 = 188$, which will be the lower limit on the c/i 0.

The maximum value possible is 240 which will be the upper limit on the c/i 0, according to assumption 3.

In the same way, going by the remaining assumptions we have the following characteristics.

The least value possible is $(1+1)*1*1 = 2$, which will be the upper limit on the c/i 9, and its lower limit is obviously 0.

Now, at level 3 extent and severity combination for 6 defects we have $(3+3)*2*6 = 72$. And at level 2, we have $(2+2)*2*6 = 48$. Referring to the classification of c/i's these values represent extensive deterioration *Table 14* and can be related to c/i's 4 and 5 respectively.

And at level 1 extent and severity combination, we have $(1+1)*2*6 = 24$, representing the lower limit on the c/i 6.

Now, so far we have:

Range	Category
9 = 0 to 2	Light
8 = ? to ?	Deterioration
7 = ? to ?	
6 = 24 to ?	Moderate
5 = 48 to ?	Deterioration
4 = 72 to ?	Extensive
3 = 96 to ?	Deterioration
2 = ? to ?	Structurally
1 = ? to ?	Inadequate
0 = 188 to 240	

The rest of the limits can be deduced based on the remaining assumptions as follows;

The difference between the upper limit of the upper c/i and the lower limit of the lower c/i is 1. Therefore the lower limit on c/i 8 is, *2+1 = 3*. And the upper limit on c/i 6 is, *48-1 = 47*. Similarly, on c/i 5 it is 71, on c/i 4 it is 95 and c/i 1 it is 189.

Now to find the remaining limits; in each category the relationship is considered linear. In category 1 the increment on the upper limit and the lower limit is calculated as follows:

(Lower limit value on c/i 6 - lower limit of c/i 8)/(Difference in c/i values)

which is, *(24 - 3)/(8 - 6) = 10.5*

Therefore c/i 7 has a lower limit *3+10.5 = 13.5*, rounded to 14. And c/i 8 has an upper limit of *14 - 1 = 13*. The upper limit on c/i 7 is obviously, 23 (24 - 1).

In category 4 the increment or the step size is:

(188-96)/(3-0) = 30.67

Therefore the lower limit on c/i 2 is, *96 + 30.67 = 127* and c/i 1 has, *126 + 30.67 = 157* as its lower limit. In the same way all the remaining limits on the condition indices are found and the relationships are given below.

C/I	Range
9	*0 - 2*
8	*3 - 13*
7	*14 - 23*
6	*24 - 47*
5	*48 - 71*
4	*72 - 95*
3	*96 - 125*
2	*126 - 156*
1	*157 - 187*
0	*188 - 240*

Dividing into categories we have; Figure 35, page 95

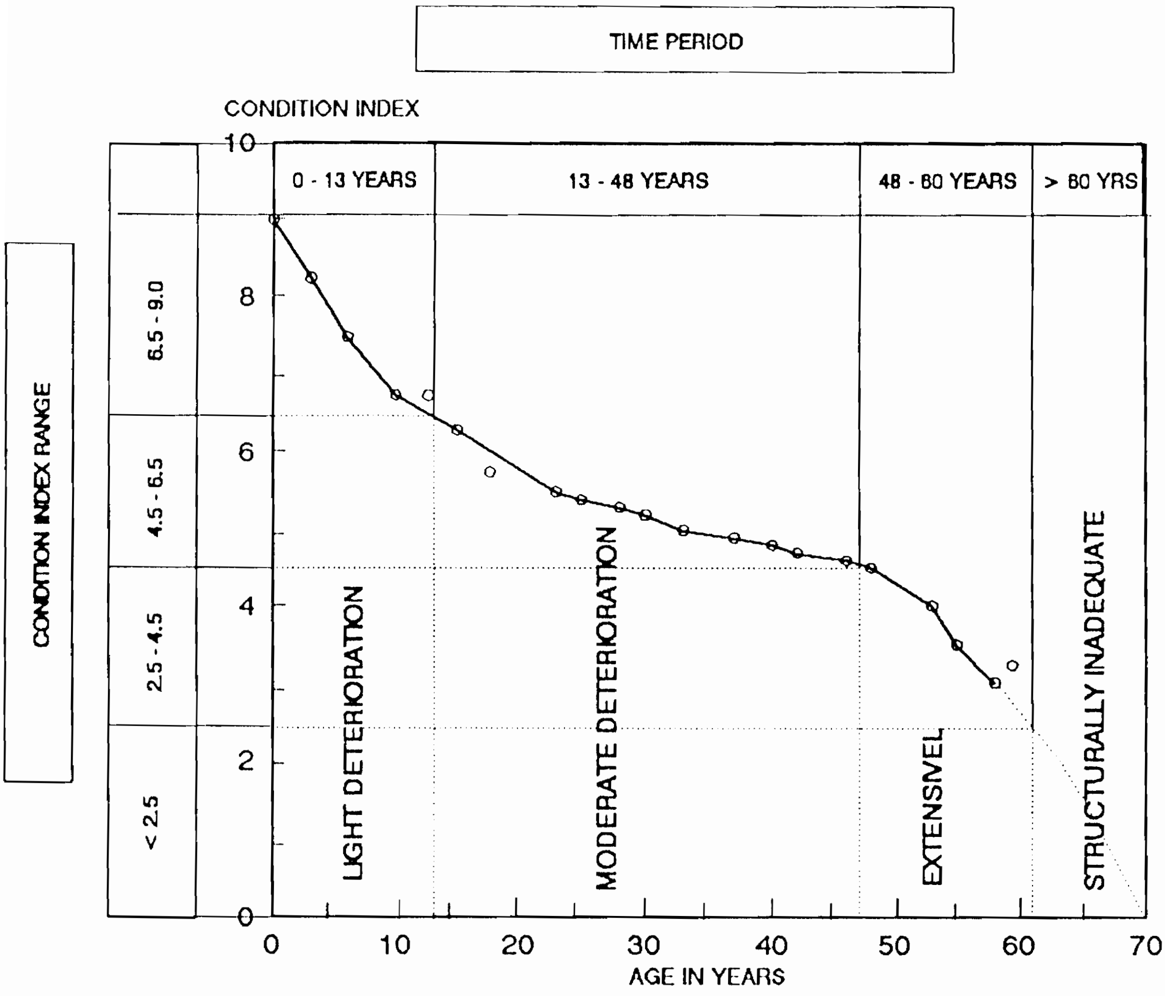


Figure 35 C/I Categories, Age and Failure Probability Ranges.

4.0 PROBLEM BUILD UP AND ANALYSIS

4.1 Focus

Bridges with reinforced concrete decks form approximately 20 percent of the total bridges in U.S. Structural adequacy is okay and the loss of 9 safety index points is mainly due to deck deterioration. Functional obsolescence is evident but not dealt with here. The service life is half up and replacement has been suggested to major components like the decks. NBI statistics further state 67 percent of all the bridge types need to be replaced and 18 percent need rehabilitation. Rehabilitation is defined as that repair work which involves considerable amount of detailed inspection to ascertain the magnitude of the problem before a major repair is envisaged, and involves economic evaluation of the various alternatives, before deciding on the appropriate repair work. Rehabilitation can be state of the art or that remedial measure which is not common and usually has a longer service life and involves a large expenditure.

Replacement seems to be unduly high. There is no clear and systematic methodology which can be followed to quantify the condition of the bridge deck and to decide whether replacement, which is defined as the removal of the older disintegrated or structurally inadequate component or subsystem to restore the structure to the desired level of serviceability, is required or rehabilitation can be sufficient. As indicated in the literature survey on BMS, life cycle cost analysis is required to be performed to decide between replacement, repair and or rehabilitation and to choose among the very many MR&R procedures available. But, before doing this, a detailed investigation of the bridge deck condition using sophisticated and the latest instrumentation and failure detection techniques is very important. This can be possible only when there is a methodology available which can help get first hand information of the existing deck deterioration problem with an easy to understand, simple systematic narrative and graphical description of the failure modes and the defects causing deterioration, the factors, remedial measures and failure mitigation procedures. reliability probability or failure probability range is an indicator of the seriousness or magnitude of the deterioration problem. Should the reliability after deterioration be known, this could be the first step toward a detailed deck condition evaluation and structural analysis. And a decision to repair, rehabilitate or replace can then be taken after performing a life cycle cost analysis to decide the best strategy.

A brief discussion on the outputs from each of the modules in the methodology is given below:

- The FMEA identified structural inadequacy as one of the failure modes and identified deterioration as the primary cause to this problem. Table 2, It points to the deck as the prime candidate for deterioration and gives insight to the very many failure detection methods and failure mitigation techniques available to perform a detailed condition evaluation of the bridge and bridge deck.

- The FTA isolated the various defects contributing to deck deterioration Fig. 12 and highlighted the various factors causing these defects. A probability of failure or a failure probability range had to be developed for the bridge deck failure which was not possible in the FTA due to lack of priori failure probabilities.

- The Decision Tree, Fig. 31 working on the information provided by the Special Tables on the significance extent and severity of each defect, was able to arrive at a cumulative numerical value for the magnitude of deterioration due to various defects, which is related to the condition index range, which, in turn is related to the service life range and the failure probability range. Fig. 34

An example problem following the working of the decision tree is provided below.

Visual inspection yielded transverse cracking in the deck, classified as extensive and not severe, leaching from underneath the deck, classified as frequent and moderate, corrosion, with electrical potential none > 0.35 and chloride content > 2.0 per cubic yard, few but severe delaminations, intermittent and not severe popouts and few but severe scales.

Solution: Referring to the Special Tables A and B:

Deck deterioration only, number of defects = 6. They are transverse cracking, leaching, corrosion, delaminations, popouts and scaling.

Referring to the Decision Tree: The magnitude of deterioration based on extent, severity and significance is:

$(4+1)*2 \ + \ (3+2)*2 \ + \ (2+3)*2 \ + \ (1+3)*2 \ + \ (2+1)*1 \ + \ (1+3)*2$

That is, $10 + 10 + 10 + 8 + 3 + 8 = 49$

Conclusions: Referring, *Figure 35* it can be concluded;

- Extensive deterioration category.

- Condition rating is 5.

- Approximate age is 40 years.

5.0 SUMMARY, CONCLUSIONS AND FURTHER RESEARCH

5.1 Summary

Bridges with reinforced concrete deck form approximately 20 percent of the bridges in the United States.

Structural adequacy is okay and the loss of 9 safety index points is mainly due to deck deterioration. Functional obsolescence is evident but not considered here. The service life is half up and replacement has been suggested to major components like the decks for a lot of bridges.

NBI statistics state 67 percent of all the bridge types need to be replaced and 18 percent need rehabilitation. Replacement seems to be unduly high. There is no clear and systematic methodology which can be followed to quantify the condition of the bridge deck and to decide whether replacement is required or rehabilitation can be sufficient. As indicated in the literature survey on BMS, life cycle cost analysis is required to be performed to decide between replacement, repair and or rehabilitation and to choose among the very many MR&R procedures available. But, before doing this, a detailed investigation of the bridge deck condition using sophisticated and the latest instrumentation and failure detection techniques is very important. This can be possible only when there is a methodology available which can help get first hand information of the existing deck deterioration problem with an easy to understand, simple systematic narrative and graphical description of the failure modes and the defects causing deterioration, the factors, remedial measures and failure mitigation procedures. This information can suppliment the visual inspection and detect many defects to their root. Failure probability/reliability probability range is an indicator of the seriousness or magnitude of the deterioration problem. Should the reliability after deterioration be known, this could be the first step toward a detailed deck condition evaluation and structural analysis. And a decision to repair, rehabilitate or replace can then be taken after performing a life cycle cost analysis to decide the best strategy.

5.2 Conclusions

Going by the goal set to achieve a simple methodology to find failure probability range for deck deterioration, the following can be concluded.

The methodology makes use of a series of different modules, each different in structure and representation, but simple enough to understand, with each module resulting in an output which is the input for the subsequent module. This is important, to indicate continuity and moreover, to arrive at the desired results; that being 1) To identify the defects causing deck deterioration, which is, 2) Recognized as one of the cause for structural instability, and 3) To quantify these defects to arrive at a numerical value, which establishes the condition of the deck and helps identify the approximate age of the deck and the reliability after these defects.

Right now, structural deterioration is serious in the United States requiring billions of dollars in maintenance and repair funds. And any step taken to identify the problems faced in bridge management system to conserve and seek solutions to the challenging maintenance and rehabilitation situations posed, to maintain this large and diverse infrastructural facility for some more years is welcome. The methodology identified here can be opening up a new approach to the bridge deck problem and can be further refined and tested to suppliment the visual or routine inspection now currently being done by bridge inspectors on concrete decks. The methodology can be the first step toward a much larger and comprehensive detailed inspection which follows the routine inspection to quantify the deck deterioration problem and to suggest the right type of maintenance and or rehabilitation decision.

5.3 Research Needs

Much hasen't been told about Failure Mitigation in the FMEA. Only the broad definitions of repair and replacement are included. Further research towards identifiying the routinely used and the latest methods of bridge deck maintenance, repair and rehabilitation need to be investigated and included in the module for specific deterioration causing defects.

The importance and emphasis on good design and construction practice needs to be stressed. If these causes can be further analyzed just like the deterioration cause, then they could be an important suppliment to the decision tree.

Only the deck and especially the reinforced concrete bridge deck in the bridge system has been investigated for this study and a methodology is been proposed to analyze only the deterioration problem faced by the deck. There is a need to develop a methodology in the similar manner for the superstructure, the substructure and the remaining important subcomponents of the bridge system.

Markov Chains have proved to be an important analytical tool to predict deterioration and hence deterioration failure probability. But the data sample needs to be large to capture the effect of environment on bridges across the country where different climatic conditions exist, so that the deterioration graph can be smoother and truly representative of the deterioration of concrete bridges around the country.

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ABSTRACT

Bridges in the United States and throughout the OECD countries are deteriorating at a very rapid rate. Bridges with reinforced concrete decks are no exception. Decks, more than any other component or subsystem in the bridge system has deteriorated the most requiring immediate repair, rehabilitation or replacement to maintain them at the desired level of serviceability which, at present require billions of dollars. Design inadequacy, bad construction practices, poor quality materials, nonuniform maintenance and repair, increase in traffic volumes and higher axle loads besides the influence of the environment, and the application of deicers are considered to be the factors contributing to deterioration of the deck. Deterioration is serious, and corrosion, scaling, spalling, leaching etc., are the very many indicators of deterioration.

A methodology consisting of a number of modules identifying the failure modes, effects, causes, failure mitigation and detection procedures, and a simple graphical method to identify the indicators of deterioration and quantify them based on extent, severity and significance for each defect, and then to relate the effect of each combination of extent, severity and significance to condition index range, with the ultimate objective to find the failure/reliability range is required, before undertaking a detailed condition evaluation and structural appraisal of the deck, to decide on the right type of maintenance, rehabilitation and or replacement decision. In this study an attempt is made to predict failure probabilities due to deterioration for reinforced concrete bridge decks and to find the associated service life range, so that this information can become useful in the much larger and comprehensive Bridge Management System designed solely for the maintenance and rehabilitation of the vast number of concrete bridges found in this country and elsewhere.