The Columbus Drive Bascule Bridge
and
Recommended Modification to AASHTO Movable Bridge Specifications Related to Stress Concentrations in Keyways

A Paper Presented to the
Machinery and Mechanisms Session
at
The First Biennial
Symposium and Exhibition
on
Movable Bridge
Design and Technology

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November 4, 1985

1. PURPOSE

The purpose of this paper is two fold. First, it will provide an overview of the planning, design and construction of the Columbus Drive Bascule Bridge in Chicago, Illinois. This bridge is the longest and widest movable bridge in Chicago and one of the largest bascule bridges in the world. And, secondly this paper will point out articles in the American Association of State Highway and Transportation Officials (AASHTO) "Standard Specifications for Movable Highway Bridges" that are related to the stresses in the corners of keyways and which the author believes should be considered for clarification, modification and amendment. This belief is based on experience gained in the investigation of a pinion gear failure that occurred on the Columbus Drive Bridge.

2. EARLY PLANNING AND PRELIMINARY DESIGN

The Columbus Drive Bascule Bridge is the main link between the Illinois Center Air Rights Development and the New Streeterville Development which is proposed north of the Chicago River in Chicago, Illinois. The I.C. Air Rights Development is an 83-acre city within a city located on the former Illinois Central Railroad Yard south of the Chicago River.

The I.C. Air Rights Development was provided with a innovative tri-level roadway network in order to minimize traffic congestion. The concept was to provide for local traffic on the upper level, through traffic on the intermediate level, and truck and delivery traffic on the lower level. The Columbus Drive Bascule Bridge carries roadway and pedestrian traffic across the Chicago River at the intermediate level.

The bridge provides a new major North-South through street which is parallel to and halfway between Michigan Avenue and Lake Shore Drive. The Columbus Drive Bridge, which is the first bascule bridge at a new Chicago River location in over 40 years, carries seven lanes of traffic, three lanes in each direction and a left turn lane, along with two ten foot sidewalks.

The new Columbus Drive extension is currently being utilized as a detour for traffic during construction to eliminate the 90-degree turns on Lake Shore Drive.

The Columbus Drive Bridge is the longest and widest movable bridge in Chicago and is one of the largest bascule bridges in the world. The bridge is approximately 270 feet between trunnions and the movable part is 110 feet wide. Clearance for ships is 21 feet above Chicago City Datum for a width of 177 feet.

The AASHTO "Standard Specifications for Movable Highway Bridges" was utilized in the design of the bridge along with supplemental requirements from the City of Chicago.

The movable part main supporting members are box girders rather than the more conventional trusses utilized throughout Chicago. The conventional design for a bascule bridge is to locate through trusses at the outside of the operating lanes. The roadway is supported by floorbeams spanning between the trusses and the sidewalks are carried by brackets cantilevered from the trusses. Since the Columbus Drive design called for seven lanes of traffic, the use of through trusses located at the curb lines was not feasible. Another alternative would be to design for three through trusses thus cutting the floorbeam span in half. However, location of through trusses along the centerline and curb lines of the bridge would create a safety hazard to traffic, reduce sight distance, especially for turning vehicles, and detract from the appearance of the structure. Therefore, to design an aesthetically pleasing structure with adequate clearance for river traffic under the bridge, but without the hazardous trusses projecting above the deck, it was decided that four box girders located completed under the deck would be utilized to support each leaf.

The goal was to design an aethestically pleasing structure that would blend with the modern redeveloped area. This was accomplished by designing the box girders with one field splice per member. Because of the size of the bridge and uniqueness of the design, an investigation was made to determine the feasibility of constructing such a structure. The outcome of the investigation was a proposed construction sequence for the box girders, (see Figure 1).

This construction sequence called for the erection of the main box girders in five stages:

STAGE 1 - Construct foundations and erect trunnion columns.

STAGE 2 - Erect anchor arm. (In the schematic drawing only two of the four anchor arms are shown.)

STAGE 3 - Erect trunnion girders by threading through the anchor arms.

STAGE 4 - Position trunnion bearings.

STAGE 5 - Erect counterweight boxes and river arm.

During construction the sequence was modified by the introduction of two field splices in the lower chord of each anchor arm. Thus allowing Stage 2 to be the erection of the trunnion girders, followed by positioning of trunnion bearings, and then the erection of the anchor arms by twisting them over and around the trunnion girder.

3. SUBSTRUCTURE

The bascule pit provides space for the counterweight when the bridge is in the up position. The bottom of the pit floor is located approximately 28 feet below the ground surface and the pit walls and slab are designed for full hydrostatic head of water. Consequently, the pits are massive concrete structures. The river wall is seven feet at the base and the counterfort approximately thirteen feet. The pit slab is 4.5 feet thick. Each pit is supported by 23 caissons, ranging in size from four to seven feet in diameter.

4. MOVABLE PART SUPERSTRUCTURE

One of the most notable features of the bridge is the use of box girders instead of the more traditional trusses for the main moveable part members. Each box girder is composed of two parts: the river arm and the anchor arm.

Even though the anchor arm resembles a truss it is actually a welded frame. The openings in the anchor arm were introduced to reduce the weight of the box girders and to provide space for the rack and pinion drive system. The trunnion is located at the center of the anchor arm.

Because the anchor arm assembly is actually a rigid frame, there was concern that residual stresses would be induced by welding, especially if full penetration welds were required. A study of the residual stresses was made and it was determined that partial penetration welds would be advantageous for certain portions of the box girder. The use of partial penetration welds not only reduced the fabrication costs but also resulted in a reduction of total stress, particularly in some of the critical areas of the anchor arm.

Connecting to each anchor arm to complete the main girder is a river arm. Each river arm is 2.5 feet wide and 121 feet long. The depth varies from four feet at the center break to twenty two feet at the field splice with the anchor arm. The flange plates are from 1-1/2 to three inches in thickness and the web plates vary from one to two inches. Each river arm weights 92 tons.

The connection between each anchor and river arm required 484 - 1-1/4 inch diameter A490 high strength bolts and 74 - 7/8 inch diameter A325 high strength bolts.

Each leaf weights 6.3 million pounds. To balance the weight of the river arm about the trunnion a counterweight is provided at the back of the anchor arm. The counterweight on the Columbus Drive Bridge consists of a steel counterweight box which is filled with steel slabs and heavy weight concrete. A total of 3,000 tons of concrete counterweight was required. The concrete counterweight has pockets formed in it for placement of cast iron counterweight blocks which are used to fine tune the balancing and provide for future modifications to the bridge.

5. MACHINERY

The machinery for operating the bridge consists of two rack and pinion gear drive systems per leaf, (See Figure 2). Each gear train includes an 150 horsepower main drive motor, which is coupled to a horizontal right angle speed reducer with cross shaft output to a pinion gear. This pinion, which has a pitch diameter of 22.282 inches, meshes with a 103.451 inch pitch diameter spur gear which is on a common shaft with the main rack pinion. The rack pinion has a 37.879 inch pitch diameter and it is made from ASTM A668, Class D forged carbon steel. The rack has an 18 foot pitch radius and it is machined from ASTM A27, Grade 70-36 cast steel. The overall speed ratio from motor shaft to rack pinion shaft is 283 to 1.

The spur gear is machined from the same grade cast steel as the rack, while the pinion off the main drive speed reducer is made from the same forged carbon steel as the rack pinion. The rack pinion shaft is composed of ASTM A668, Class D forged carbon steel.

Off a cross shaft from the main drive speed reducer is a 40 horsepower auxiliary drive system. The 40 horsepower motor drives a right angle speed reducer. The two reducers are connected by a clutch or cut out coupling which is utilized to disengage the auxiliary system when the main drive system is used. The speed ratio from 40 horsepower motor shaft to rack pinion shaft is 2830 to 1.

The 150 horsepower motors are capable of opening the bridge in 80 seconds, while the time of operation for the 40 horsepower back-up system is approximately five minutes. The bridge is designed to be opened by just one of the 150 horsepower motors in an emergency.

Each of the four gear trains has three brakes. Two motor or service brakes, one for each motor, and one machinery brake. The machinery brake is located off the cross shaft of the main speed reducer.

Split type pillow block bearings with bronze bushings were used throughout.

The trunnions are made from 24 inch diameter ASTM A668, Class D forged carbon steel. They are fitted into a hole in the central part of each anchor arm. The trunnion bearing stand over five feet tall and are made from cast steel with bronze bushings.

The anchor bolts for the machinery are as large as 3-3/4 inches in diameter and 12 feet 9 inches long.

6. CONTROL SYSTEM

The bridges primary control system is a thyristor control system or speed control type system operating the 150 horsepower wound rotor motors. As a back-up each 150 horsepower motor has a stepped resistor or torque control type system. A stepped resistor control system is also utilized to operate the 40 horsepower auxiliary motors.

7. CONSTRUCTION

The construction of the Columbus Drive Bascule Bridge began in the summer of 1980. The total cost of construction was approximately $33 million. One of the most notable points during the construction was the utilization of a barge mounted, 150 ton crane for the erection of the larger structural steel and machinery components.

Because each bascule girder had just the one point of adjustment between the river arm and anchor arm, closer than normal tolerances were specified for the fabrication of the girders. Through the combined efforts of the steel fabricators and the steel erector near perfect alignment between the girders of each leaf was achieved.

On October 18, 1982, the Columbus Drive Bridge was dedicated to the memory of Police Officer William P. Fahey, who died in the line of duty as a result of a gunshot wound earlier that year. And on October 31, 1985 the bridge was officially opened to traffic.

8. RACK PINION FAILURE

For the most part the construction phase of the project was uneventful. However, on March 10, 1983 while the Contractor was conducting a training session for City of Chicago bridge operators and maintenance personnel, difficulty in operating the north leaf was experienced. Upon investigation into the machinery room it was discovered that the northeast rack pinion had factured into two pieces through the hub. Each of the fractures was located at the corner of the two keyways that was provided in the gear hub. (See Figure 3).

9. MODIFICATIONS TO AASHTO MOVABLE BRIDGE SPECIFICATIONS

An investigation into the cause of the failure was immediately undertaken by the City of Chicago and also the Contractor. A final determination as to the cause of the failure has not been made. The purpose of this paper is not to determine the cause of the failure but instead to point out provisions of the AASHTO "Standard Specifications for Movable Highway Bridges" which are related to this gear failure and which in the authors opinion should be clarified, modified or expanded. The investigation and recommendation for modification of each of the provisions listed below should be the topic of a committee effort which could be presented as a paper for consideration to AASHTO.

2.5.11 - Unit Stresses in Machinery Parts

The materials listed for use in machinery parts are for the most part not the highest strength nor the finest quality materials available today. It is recommended that higher strength and better quality materials be included in this article for consideration by the designer. Supplemental provisions on the quality of material should also be included such as provisions for Charpy V-Notch requirements to control brittle fracture and provisions for the control of inclusions.

This article also includes provisions for stress concentrations caused by keyways but does not make it clear whether or not the corners of the keyways must be filleted. The ANSI Standard on "Keys and Keyseats" USAS B17.1 indicates that "*In general practice*, chamfered keys and filleted keyseats are not used. However, it is recognized that fillets in keyseats decrease stress concentrations at corners". The ANSI Standard goes further to suggested sizes of fillets and chamfers on the keys based on keyway depth. It is recommended that the use of filleted keyways and chamferred keys be investigated and be considered for inclusion into the specifications.

2.6.15 - Hubs

Should the provision that the hub length be not less than 1.25 times the width of the teeth for gear wheels apply to pinion gears? The problem with nomenclature (gear wheels) could be eliminated by the inclusion of a definition of terms article and the proper use of these terms throughout the specification.

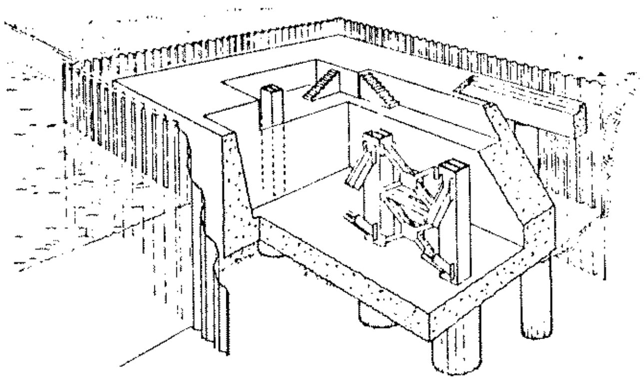
> This provision further states that, "The thickness of the hub, preferably, shall be not less than 0.4 of the diameter of the bore". It is not clear, however, whether this thickness is to be measured through the full hub thickness or at the reduced section at a keyway.

The above articles have been singled out because their provisions were sited as possible causes for the gear failure, based on a particular interpretation. The author is confident that the original design of the machinery was correctly performed but that the interpretation of various AASHTO specification provisions clouded the real cause or causes of the gear failure.

It should be noted that the gear that failed was replaced utilizing the same design, except the Contractor elected to provide fillets in the corners of the keyways, and the gear has been periodically inspected and has functioned properly since the bridge was reopened in November 1983.

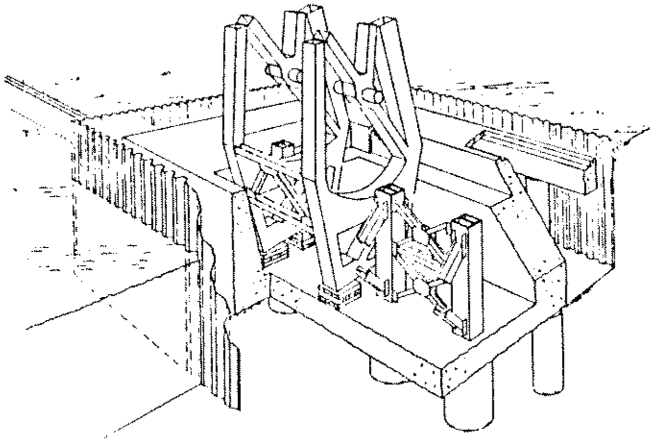
10. CONCLUSIONS

A number of modifications to articles contained in the AASHTO Movable Bridge Specifications have been presented. However, as anyone, who has ever designed a structure based on this specification, knows these are not the only provisions that could be considered for revision. It is strongly recommended that a committee be established to meet the symposiums GOAL of drafting recommendation to the existing design criteria for movable bridges maintained by AASHTO. This committee should have prior approval of AASHTO to perform this task, and should meet on a regular basis to present specifically assigned recommendations for modifications to the specifications.



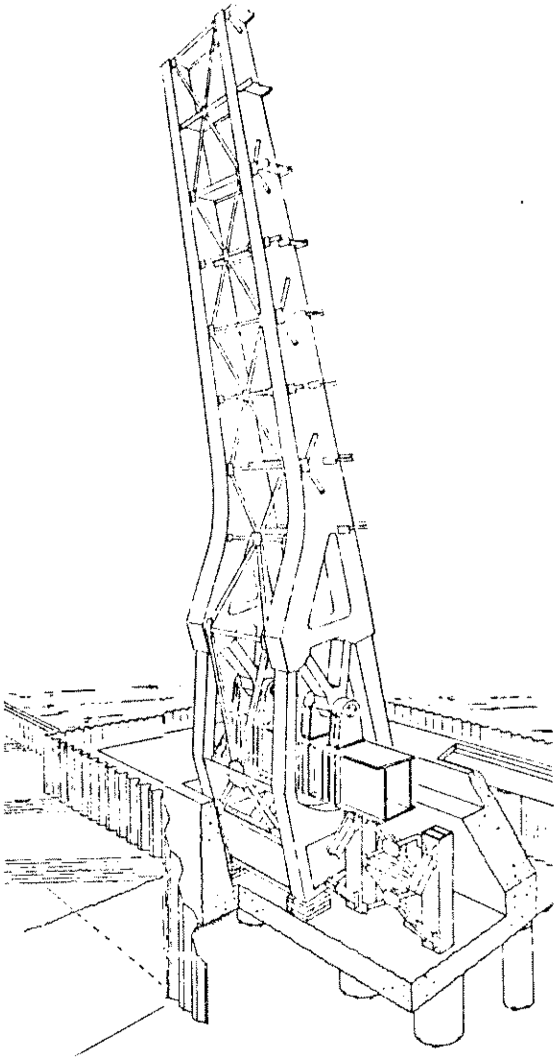
STAGE 1

CONSTRUCT FOUNDATIONS
AND PLACE COLUMNS



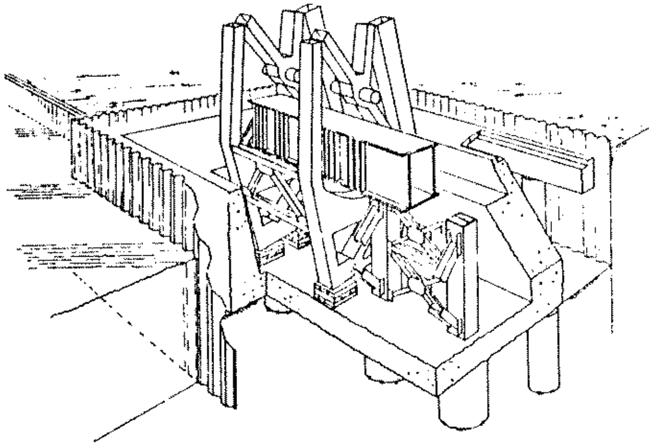
STAGE 2

PLACE ANCHOR ARMS
AND ADJUSTABLE SUPPORTS



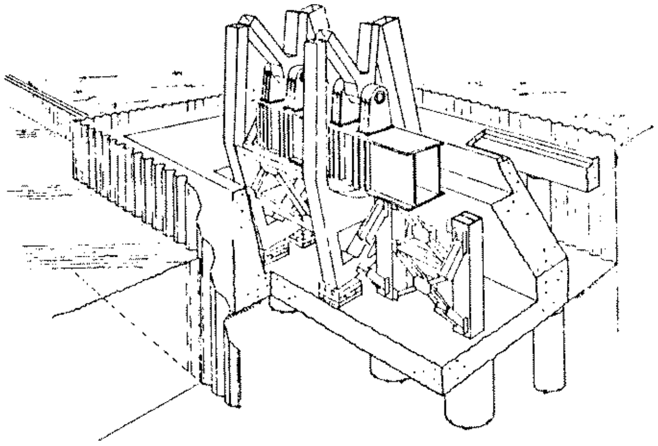
STAGE 5

CONSTRUCT COUNTERWEIGHT
AND ERECT RIVER ARM



STAGE 3

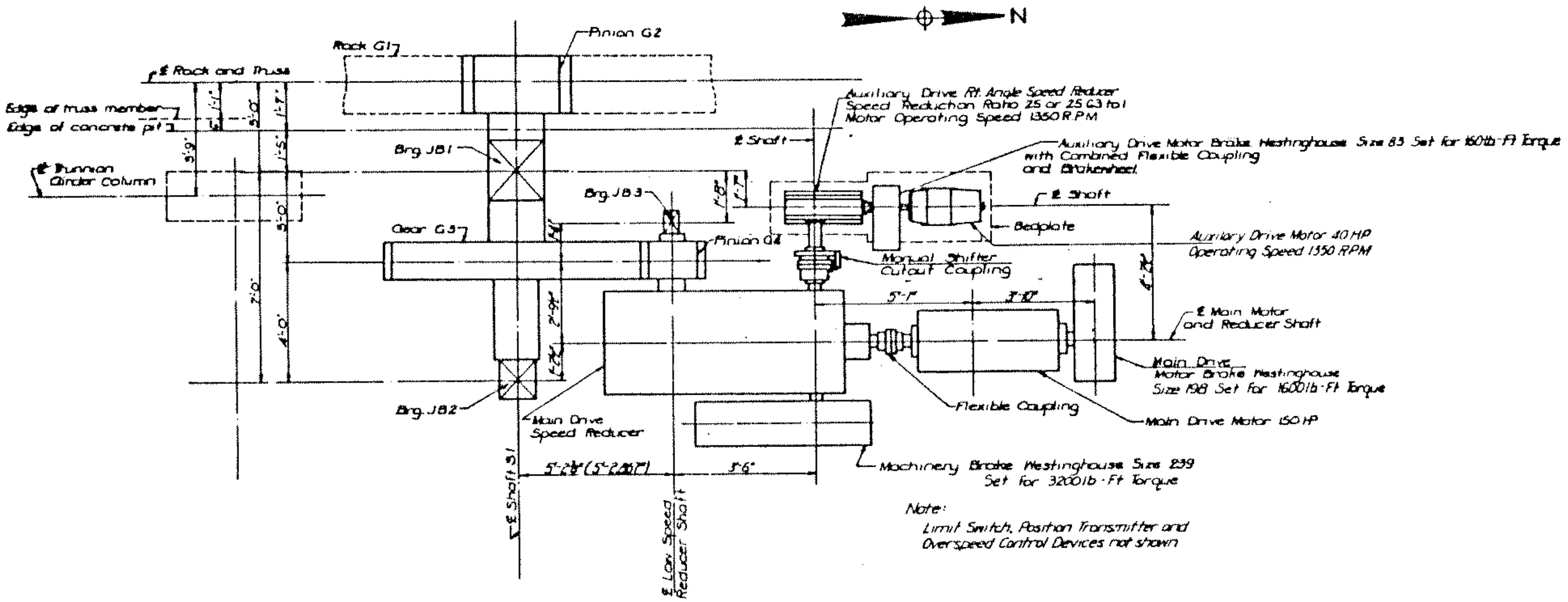
INSTALL TRUNNION GIRDER
THROUGH ANCHOR ARMS



STAGE 4

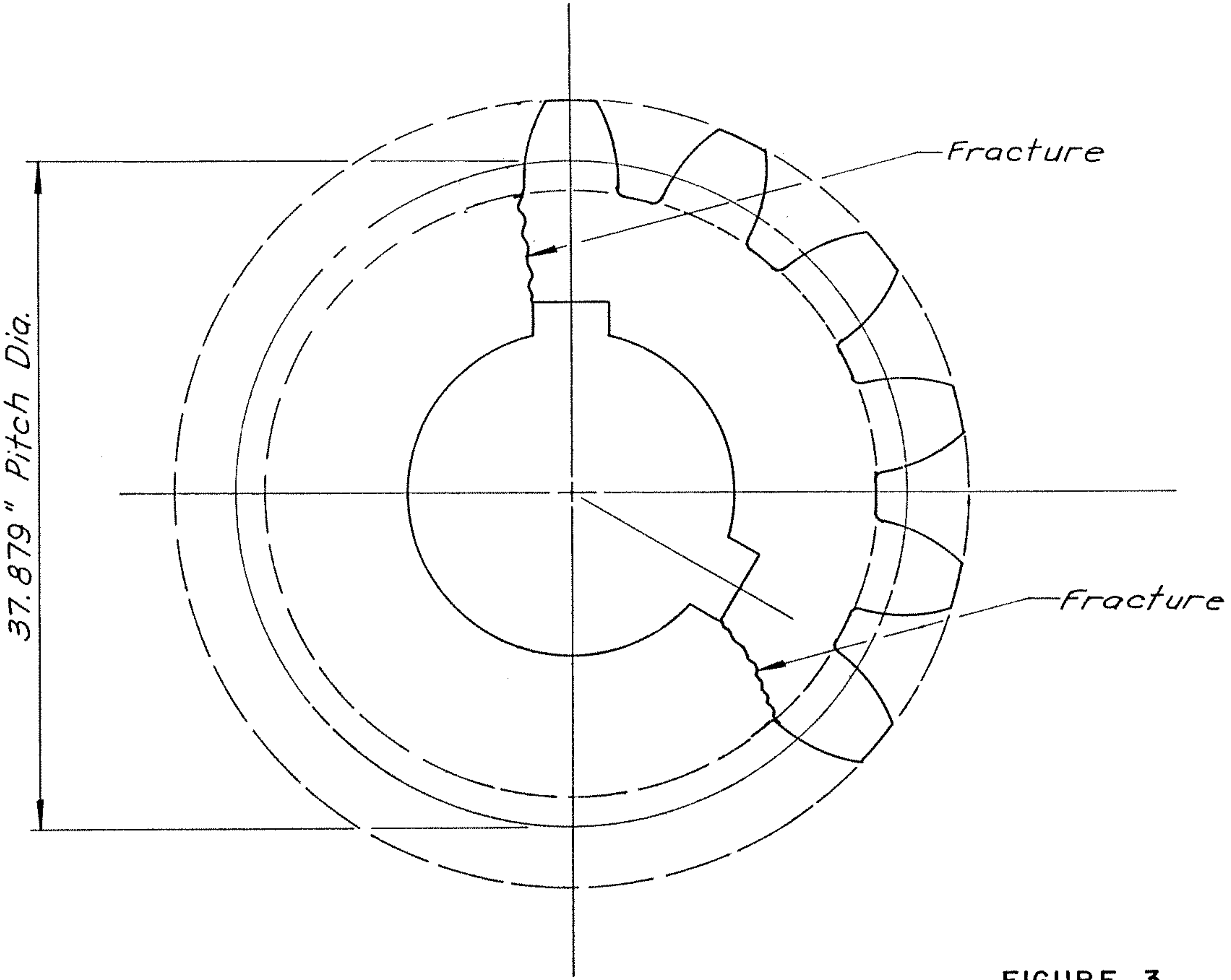
POSITION TRUNNION BEARINGS
AND SEAT TRUNNIONS

FIGURE 1



PLAN

FIGURE 2



RACK PINION

FIGURE 3