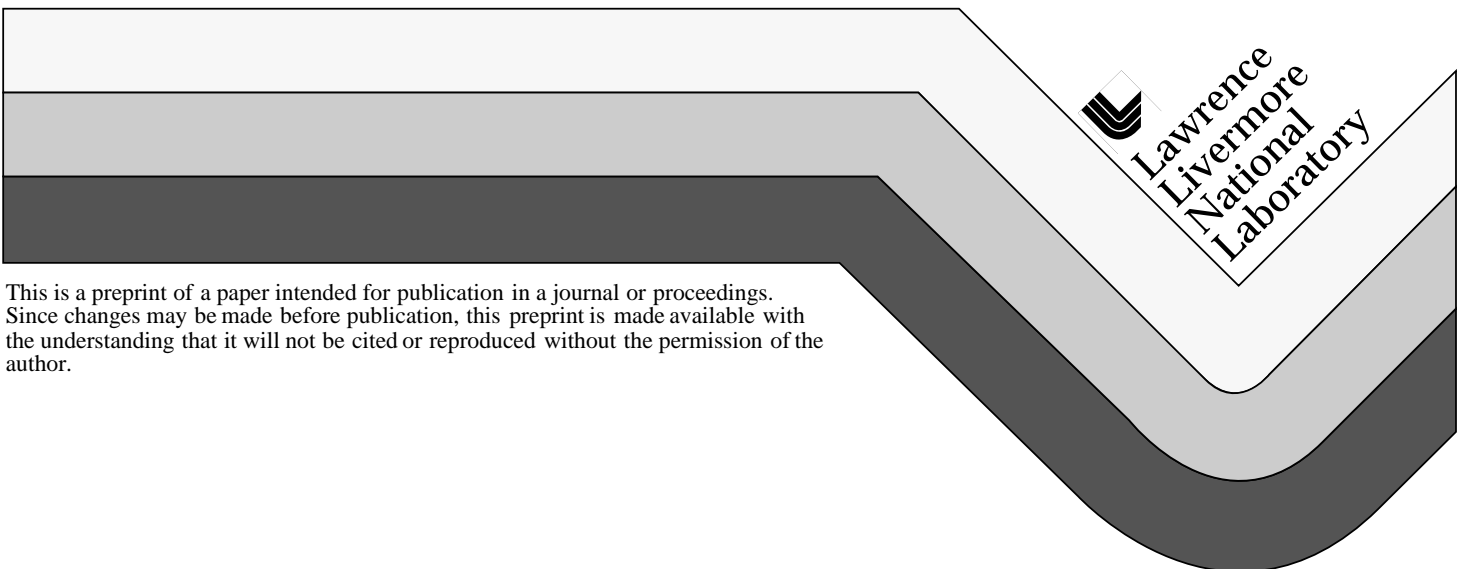# Computed Tomography of Bridge Pins,
Cast Aluminum Automotive Components and Human Joints

Harry E. Martz

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Computed Tomography of Bridge Pins, Cast Aluminum Automotive Components and Human Joints

Harry E. Martz
Lawrence Livermore National Laboratory
Engineering Directorate, L-333
7000 East Avenue
Livermore, California 94550 USA

Abstract

X-ray computed tomography (CT) imaging techniques in nondestructive evaluation (NDE) have seen increasing use in an array of industrial, environmental, military, and medical applications (Goebbels, et al., 1999). A brief overview and three diverse application studies of x-ray CT at the Lawrence Livermore National Laboratory (LLNL) will be discussed. (1) Bridge pins are fracture critical elements for some multi-span steel bridges. Recently, pins were removed from their hanger pin assemblies. These pins were selected for further examination by laboratory NDE techniques. High-energy x-ray radiography and CT were used to characterize these pins. (2) Cast light metals, aluminum and magnesium, are being used in an ever increasing number of applications to reduce automobile weight for improved gas mileage and lower emissions. After mechanical testing, the damage in notched Al-tensile test specimens was first determined using CT and subsequently by metallography analysis intended to benchmark the CT technique. (3) A computational approach to normal joint kinematics and prosthetic joint analysis offers an opportunity to evaluate and improve prosthetic joint replacements before they are manufactured or surgically implanted. Computed tomography data are combined with computational analysis to reveal regions where the joint design can be improved for better performance and longevity, prior to expensive manufacturing, laboratory tests, and clinical evaluation.

Introduction

Single-view (or angle) radiography hides crucial information—that is, the overlapping of object features obscures parts of an object's features and the depth of those features is unknown. Computed tomography was developed to retrieve three-dimensional (3D) information of an object's obscured features. To make a CT measurement, several radiographic images (or projections) of an object are acquired at different angles, and the information collected by the detector is processed in a computer (Herman, 1980). The final 3D image, generated by mathematically combining the radiographic images, provides the exact locations and dimensions of external and internal features of the object. Three diverse applications of CT are described in this paper.

Bridge Pins

Bridge pins were used in the hanger assemblies for some multi-span steel bridges built prior to the 1980's, and are sometimes considered fracture critical elements of a bridge. For example, a bridge pin failure was the cause of the 1983 collapse of the Mianus River Bridge that resulted in the deaths of 3 people. Bridge pins are typically made of steel, ~20-cm long with a 7.6-cm wide barrel and threaded ends of ~6-cm outer diameter. The pins typically fail at the shear plane, the region where the shear forces from the hanger plate are transmitted to the web plate, and where the majority of flaws so far are detected.

The only part of the bridge pin accessible for inspection in the field is the exterior face of the threaded portion. This makes it difficult geometrically to inspect the pins. Ultrasonic methods are generally employed in the field to inspect the pin-hanger assemblies. These methods consist of manually scanning a hand-held probe over the exposed portion of the pin. Due to geometric constraints as well as limited access to the pins, the field inspection can be difficult to perform as well as interpret, due to the subjective nature of this method. For example, critical areas of the pin are often hidden by geometric constraints, corrosion groves at the surface of the shear planes typically occur and can be mistaken for cracks, and acoustic coupling between the pins and the hangers can occur.

The Federal Highway Administration (FHWA) recently acquired several pins that were removed from a bridge in Indiana following an ultrasonic field inspection. Some of these pins were cracked and this provided the opportunity to better understand the failure mechanism(s) of bridge pins using laboratory NDE techniques. Visual inspection and laboratory inspection techniques such as ultrasonic C-scans and film radiography were performed by FHWA. Qualitatively these laboratory methods yielded similar results as found in the field inspections.

At LLNL we applied digital radiography (DR) and computed tomography characterization methods to further study the bridge pins. A 9-MV LINAC x-ray source was combined with a new amorphous-silicon, flat-panel detector (Weisfield, R. L., et al., 1998) to acquire digital radiographs of three pins and CT projections of one of the severely cracked pins. The CT data consisted of 180 projections over 180° and were reconstructed into several hundred tomograms (cross-sectional images) with a volume element (voxel) size of ~127x127x127 μm^3. Three tomograms are shown in Fig. 1. It is useful to point out that far from the shear plane, Fig 1(a), there are no apparent cracks or voids in the tomograms. Near the shear plane, Fig. 1(b), a crack appears within the pin at ~11 PM. Within the shear plane, Fig. 1(c), we observe several cracks. The large surface breaking cracks from 6 to 8 PM in Fig. 1(c) are observed visually and ultrasonically. Several smaller radial cracks are revealed in the tomograms that are not observed either visually or in the ultrasonics data. These small radial cracks, Fig. 1(c), are only in the shear plane region and most likely lead to the larger cracks, which most likely cause pin failure.
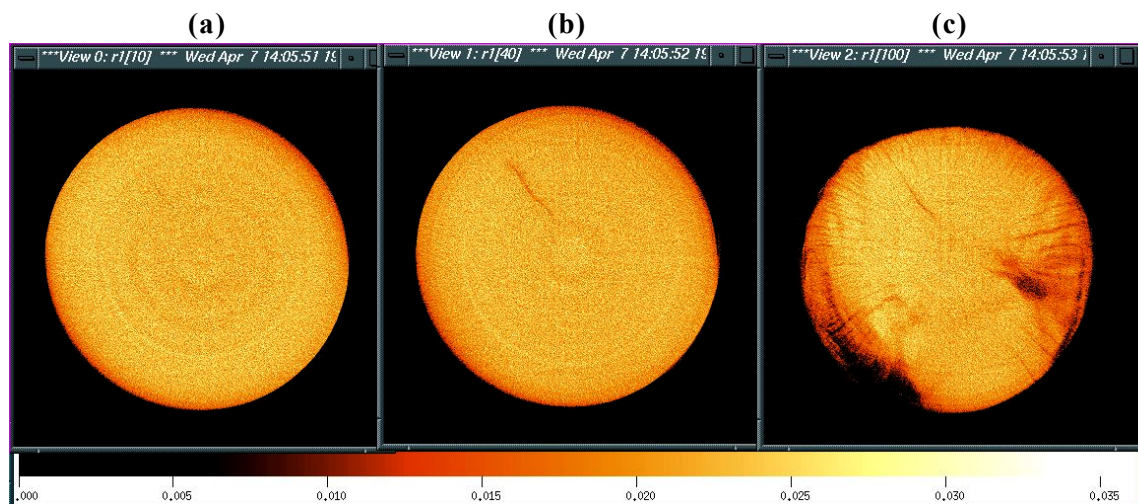

Fig. 1 Tomograms along the longitudinal axis of a cracked bridge pin. The tomograms are (a) far from, (b) near and (c) within the cracked shear-plane region. The color scale relates color tones to relative attenuation in mm^{-1} units.

Computed tomography reveals many more internal defects within the bridge pins than those observed in visual, radiographic or ultrasonic inspection. For example, we observe large and small radial cracking, and are able to measure crack sizes in all three spatial dimensions. To first order the field and laboratory ultrasonic inspection results were qualitatively corroborated by the large cracks observed in the x-ray tomograms. This provides some level of confidence in the ultrasonic field inspection method. Further work is required to quantitatively corroborate and correlate the x-ray tomographic data with the field and laboratory ultrasonic inspection results as well as to obtain a better understanding of bridge pin failure mechanisms and to improve filed inspections reliability in predicting bridge pin failure.

Cast Aluminum Automotive Components

The automotive industry has a high interest in the use of cast light metals, e.g. aluminum (Al) and magnesium (Mg) alloys, as structural components to reduce vehicle weight, and thereby increase mileage and lowering emissions. In order to promote a wider use of these cast light materials by automotive designers, it is necessary to better understand and quantify damage evolution under monotonic mechanical loading. The accumulation of damage in nearly all ductile materials subjected to monotonic loading is due to the nucleation, growth and coalescence of voids. Cast aluminum and magnesium contain pre-existing voids (porosity) due to a number of effects that accrue from the casting process. Pores exist in cast Al and Mg at different length scales ranging from sub-micrometer to several hundred micrometers, depending on formation mechanisms. The size, shape and distribution of pores have a strong influence on damage evolution, localization and mechanical properties. CT can be used to measure these properties of pores.

An ongoing study incorporates nondestructive and destructive evaluation methods with mechanical loading. Both evaluation methods are being used to study damage evolution and these results are being incorporated into constitutive equations for finite element analysis (FEA) studies to improve durability predictions (Horstemeyer, et al., 1999). These studies are performed in collaboration with USCAR (a consortium of Ford, General Motors and DaimlerChrysler), three DOE National Laboratories (Lawrence Livermore, Sandia and Oak Ridge) and the Georgia Institute of Technology.

The Al samples studied are cylindrical notched tensile bars with dimensions of 2-cm diameter grip regions on both ends, 1.2-cm diameter center notch region, and ~10-cm length. The tensile bars are machined from cast A356-alloy plates. Material surrounding the machined tensile bar was saved as side bar specimens for radiographic and metallurgical analysis, and is representative of the material in each bar prior to mechanical loading.

After mechanical loading to stress levels near failure, the damage in each tensile bar sample was first determined by porosity analysis of x-ray CT images at LLNL, followed by metallographic analysis performed by Georgia Institute of Technology. The metallography results determine small- and large-length scale damage and is useful in benchmarking the large-length scale (>20 μm) CT results. The metallographic method provides damage information for representative 2D cross sections, but is destructive and manually intensive. The CT method is capable of providing quantitative 3D damage distributions and is nondestructive, thus it preserves the sample for other analyses.
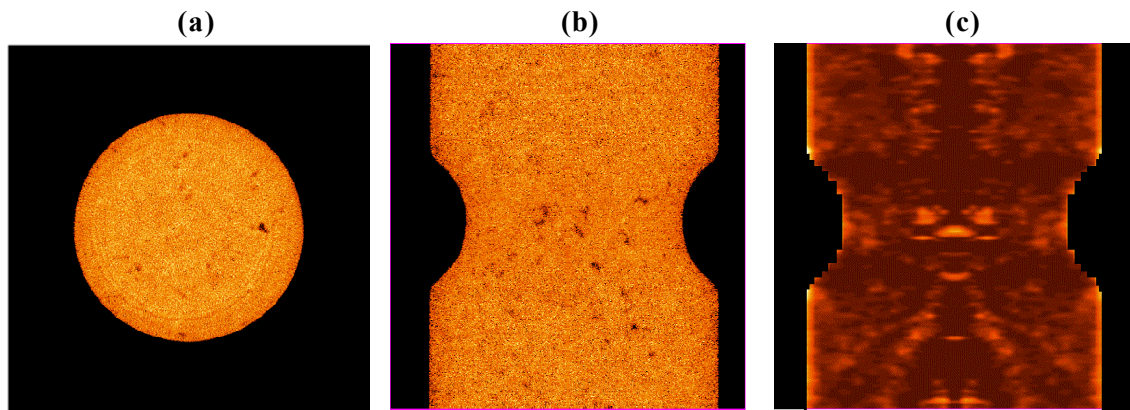
(a) **(b)** **(c)**

Fig. 2 CT results of Al-tensile test sample D19-1. The central tomograms (a) perpendicular to and (b) along the longitudinal axis reveal porosity (dark spots) within the tensile sample. (c) Image analysis results of the entire CT volume reveal the volume fraction of porosity (light colors are high porosity regions) as a function of radial and vertical coordinates.

The CT system was configured to provide a voxel size of ~20x20x20 μm^3 using a conventional 450-kV x-ray tube source operating at ~200 kV and 10 mA, and a high-density, terbium-oxide-doped glass scintillator that is lens coupled to a CCD camera detector. A geometrical projection magnification of 1.0 was used. Representative tomograms and image analysis results are given in Fig. 2. The tomograms, Fig. 2 (a & b), color tones represent the different x-ray attenuation within the Al-tensile bar sample. Since the sample can be considered to be of one composition, uniform in A356-alloy composition, these tomograms also represent the material mass density. The 3D volumetric x-ray attenuation CT data was further analyzed to provide a 2D representation of the volume fraction of porosity as a function of radial and vertical coordinates as shown in Fig. 2(c).

CT results provide 3D information on the volume fraction of porosity, and can be used to determine pore-size distributions, pore dimensions, aspect ratios and nearest neighbors at the tens of micrometers length scale. The 3D CT results have been compared to and confirmed by 2D metallurgical analysis. Our CT studies of these materials have played an important role in characterizing damage evolution under monotonic loading conditions and have been used to provide a better physical basis for setting parameters in constitutive equations for finite element analysis. Future studies with Al will involve additional tensile bar samples obtained from cast Al components.

CT studies for as cast Mg-alloy tensile samples are just beginning. Nine Mg-tensile bar samples will be characterized by CT at LLNL before they are mechanical loaded. Six will be loaded to a fraction of failure and rescanned. Three will be loaded to a fraction of failure, CT scanned, loaded again and scanned, etc. until failure. In these studies we will explore using more of the 3D aspects of the CT data, e.g., size, shape and distribution of pores. Semi-automated segmentation is being investigated to directly convert the tensile bar CT data to FEA meshes. This would allow us to study the as cast tensile bar, as in the case for the human joint FEA example below, instead of an assumed model of a tensile bar.

Human Joints

Human joints are commonly replaced in cases of damage from traumatic injury, rheumatoid diseases, or osteoarthritis. Frequently, prosthetic joint implants fail and must be surgically

replaced by a procedure that is far more costly and carries a higher mortality rate than the original surgery. Poor understanding of the loading applied to the implant leads to inadequate designs and ultimately to failure of the prosthetic (van der Meulen, M.C.H., 1998).

LLNL's approach to prosthetic joint design offers an opportunity to evaluate and improve joints before they are manufactured or surgically implanted. The modeling process begins with computed tomography data, which are used to develop human joint models (Martz, 1998). An accurate surface description is critical to the validity of the model. The marching cubes algorithm is used to create polygonal surfaces that describe the 3D geometry of the structures (typically bone) identified in the scans. Each surface is converted into a 3D finite element mesh that captures its geometry. Boundary conditions determine initial joint angles and ligament tensions as well as joint loads. Finite element meshes are combined with boundary conditions and material models. The analysis consists of a series of computer simulations of human joint and prosthetic joint behavior.

The simulations provide qualitative data in the form of scientific visualization and quantitative results such as kinematics and stress-level calculations as shown in Fig. 3. In human joints, these calculations help us to understand what types of stresses occur in daily use of hand joints. This provides a baseline for comparison of the stresses in the soft tissues after an implant has been inserted into the body. Similarly, the bone–implant interface stresses and stresses near the articular surfaces can be evaluated and used to predict possible failure modes.
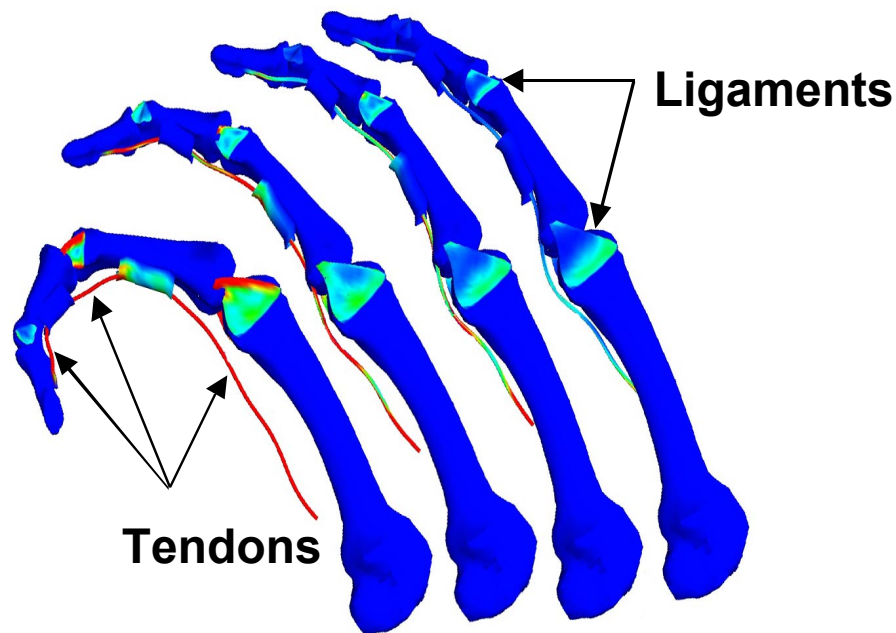

Fig. 3 Three-dimensional model of the bone structure generated from CT scans of the index finger. Different stages of finger flexion were studied by FEA. The different colors (purple/blue for low stress to red for high stress) within the tendons and ligaments indicate stresses during flexion.

Results from the finite element analysis are used to predict failure and to provide suggestions for improving the design. Multiple iterations of this process allow the implant designer to use analysis results to incrementally refine the model and improve the overall design. Once an implant design is agreed on, a prototype is made using computer-aided manufacturing techniques. The resulting implant can then be laboratory tested and put into clinical trials (Hollerbach and Hollister, 1996).

Currently, LLNL is analyzing human joint models to determine the in vivo loading conditions of implants used in normal life and implant components as they interact with each other. Future research will combine the human and implant models into a single model to analyze bone-implant interface stresses.

Conclusions

The usefulness of computed tomography for three diverse and challenging nondestructive characterization applications has been discussed. CT was useful in obtaining new insights into the failure mechanisms of bridge pins that are fracture critical elements for some multi-span steel bridges. CT is being used to help augment the laborious and destructive application of metallographic sectioning for improved modeling of the durability of new aluminum and magnesium alloys being developed for the automotive industry. Nondestructive tomographic images are being employed in human joint implant design. Studies to date have shown the utility of this new high-spatial resolution CT data to improve performance and longevity, prior to expensive manufacturing, lab tests, and clinical evaluation.

Acknowledgements

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