Title
A Methodology of Printing Notched Replica Teeth for Simulating Fatigue Cracks of Natural Teeth using Quantitative Percussion Diagnostics

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A Methodology of Printing Notched Replica Teeth for Simulating Fatigue Cracks of Natural Teeth using Quantitative Percussion Diagnostics

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Materials Science and Engineering

by

Haocheng Yang

Thesis Committee:
Professor James Earthman, Chair
Professor Diran Apelian
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2022

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Time always flies so fast that the last two years of my life, when I was a graduate student, will come to a successful conclusion in the blink of an eye. During these two years, I have been helped by many people around me, my respected teachers, my dear classmates, and my best friends. When my graduation thesis is about to be completed, and when I graduate, I want to express my gratitude to the family members who supported me in writing my thesis and to the mentors and friends who helped me.

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in my thesis. I also thank D. Hull press for permission to include the photos in Chapter one, originally published by Elsevier Press.

ABSTRACT OF THE THESIS

A Methodology of Printing Notched Replica Teeth for Simulating Fatigue Cracks of Natural Teeth using Quantitative Percussion Diagnostics

by

Haocheng Yang

Master of Science in Materials Science and Engineering

University of California, Irvine, 2022

Professor James Earthman, Chair

As we all know, teeth are typical brittle fracture material; there will be no apparent signs or painful experiences for patients to be aware of before the crack becomes challenging to control and restore. In addition, conventional dental diagnostics aids are partially effective in diagnosing structural defects such as cracks in teeth. Therefore, a new detection method, Quantitative Percussion Diagnostics, usually used to test the structure's instability, seems like a good choice for doctors to detect the crack before it goes to an irreversible status. But the natural cracked tooth samples are hard to test and analyze to get the actual cracks status of the tooth since the extraction processes produce additional cracks. In addition, most crack growth of the natural teeth is vertical downward, so if we directly fatigue the intact replica tooth, there's no way to get regular, consistent crack.

Therefore, a method of printing a notched 3D replica tooth using a glass-filled resin polymer with mechanical properties similar to dentin was established. After fatiguing on a specific machine, the replica teeth containing such a simulated fatigue crack were tested using Quantitative Percussion Diagnostics (QPD). The results were consistent with QPD data for cracked natural teeth. Besides, the NanoCT scanning results reveal that our

methodology can form a short but sharp vertical crack extending from the notch tip. It can be helpful for future research to connect the QPD test results and the internal crack status in a natural tooth.

CHAPTER 1: Introduction

1.1 The Crack and Fatigue

Before we start talking about Fatigue, I think it's important to understand what crack is. A crack may be defined as a local discontinuity produced by a fracture that can arise from the stresses generated by cooling or acting on the structure. It is a severe imperfection of different materials. Since cracks create a physical separation within solids, they significantly reduce strength, creating a considerable risk for irreversible fracture. And the fracture of a solid almost always occurs due to the development of certain displacement discontinuity surfaces within the solid. If a displacement develops perpendicular to the surface of displacement, it is called a standard tensile crack or simply a crack shown in Figure 1; if a displacement develops tangentially to the surface of displacement, it is called a shear crack, slip band, or dislocation, which is the most common defects in the crystalline materials. In addition, cracks can readily propagate through stress concentration at the tip, which can be easily exaggerated by other factors, including corrosion, fatigue, high pressure, and construction material.

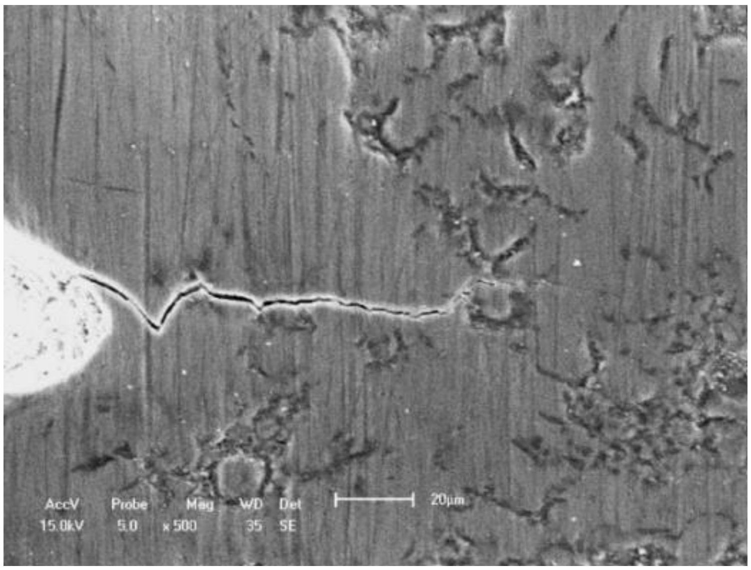


Figure 1: A example of crack initiation and propagation [1]

Structures generally have three kinds of cracks: through the crack, surface crack, and embedded crack (Figure 2).

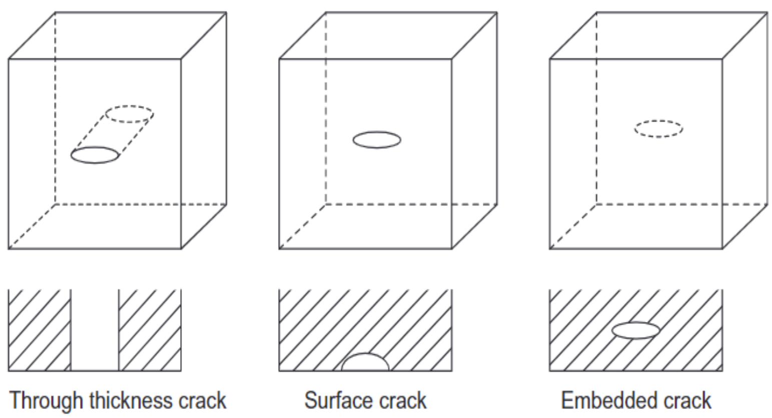


Figure 2. The position of the crack classifies crack defects.

1. Through crack: Usually, the crack would penetrate over half the thickness of the structural member. It is often simplified as an ideal crack. The curvature radius at the top of the crack tends to be zero[2].
2. Surface crack: This is where the surface of the structural member or the depth of the crack is relatively smaller than the thickness of the structural member. Generally, a surface crack is simplified as a semi-elliptical surface crack.
3. Embedded crack: This appears in the inner part of the structure and is often simplified as the elliptical plate crack or the cone crack and classified by the Shape of the Crack [2].

So the second part I want to introduce is about fatigue. Material fatigue occurs when structures fail when subjected to a cyclic load, including stresses from temperature, corrosion, load, and various other factors. This structural damage occurs even when the experienced stress range is far below the static material strength. Fatigue is the most common source behind failures of mechanical structures.

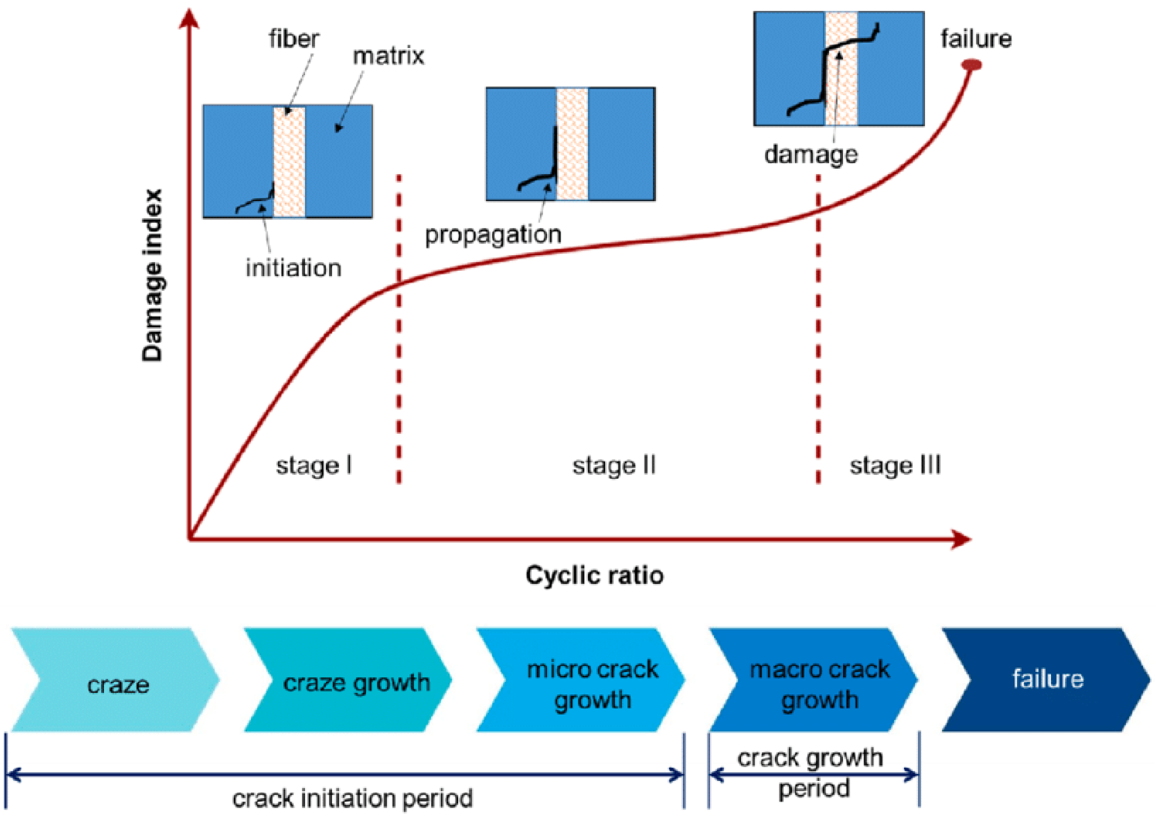


Figure 3. Stages of Fatigue Failure[3]

The fatigue process until a component finally fails under repeated loading can be divided into three stages shown in Figure 3 above.

1. During many cycles, the damage develops on the microscopic level and grows until a macroscopic crack is formed.
2. The macroscopic crack grows for each cycle until it reaches a critical length.
3. The cracked component breaks because it can no longer sustain the peak load.

For specific applications, the second stage cannot be observed. A microscopic crack instead proliferates, causing sudden failure of the component. The details of the last two stages are usually considered within the topic of fracture mechanics[3]. The term fatigue applies mainly to the first stage. There is, however, some overlap between the disciplines,d the measured number of cycles to fatigue often includes the last two stages because the most significant part of the component's life is spent before it is possible to observe a visible crack; most designs aim to avoid ever encountering such damage.

In addition, there are three typical fatigue types. First, thermal fatigue is caused by cyclical stresses resulting from fluctuations in temperature and constrained high-temperature areas. Second, corrosion fatigue is a common defect caused by cyclic stress and a corrosive environment. Fatigue in material causes cracking, which is then accelerated by surrounding corrosion, meaning defects can occur quickly and at lower loads.

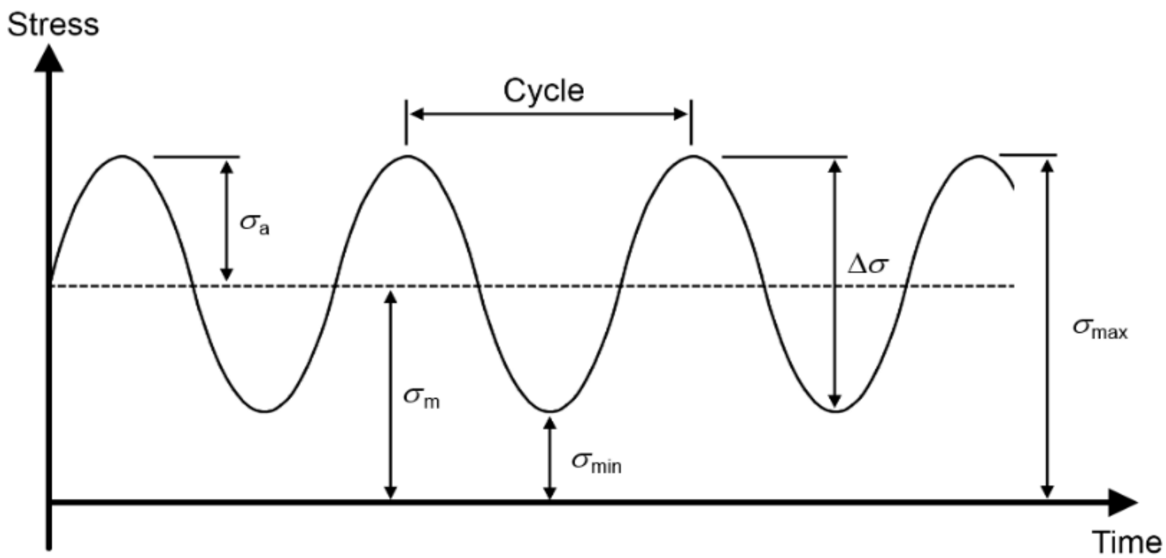


Figure 4. Standard variables used for fatigue prediction

The third is vibration fatigue which affects any subject that experiences vibration during operation and most commonly affects rotating equipment. Vibration causes the material to undergo dynamic stress, shown in Figure 4, weakening components over time and leading to load-related flaws[4].

The stress varies between maximum and minimum stress during a load cycle. In fatigue, the variation in stress is often defined using the amplitude and the mean stress. Further, variables defining the stress range and the R-value frequently describe a stress cycle. The relations between the different fatigue stress variables are shown in Figure 5.

In our Experiment, we usually set the minimum stress as 0, so the R-value can be 0 too. And the mean stress will be half of the maximum stress.

$$\sigma_{\mathrm{m}} = \frac{\sigma_{\mathrm{max}} + \sigma_{\mathrm{min}}}{2}$$

$$\sigma_{\mathrm{a}} = \frac{\sigma_{\mathrm{max}} - \sigma_{\mathrm{min}}}{2}$$

$$\Delta\sigma = \sigma_{\mathrm{max}} - \sigma_{\mathrm{min}}$$

$$R = \frac{\sigma_{\mathrm{min}}}{\sigma_{\mathrm{max}}}$$

Figure 5. The relationships between variables[4]

In summary, the presence of a crack can significantly reduce the strength of an engineering component due to brittle fracture, as already discussed above. A minor initial present flaw develops into a crack and grows until it reaches the critical size for a brittle fracture. Crack growth can be caused by cyclic loading, a behavior called fatigue crack growth.

1.2 Traditional Dental Diagnostics Aids

Our life expectancy has increased with medical techniques, and we enjoy life more than ever. This leads to our teeth staying with us longer and becoming more critical to our lives [5]. But as more and more foods are designed based on human instinct, for example, foods high in fat and sugar. People's dental health is constantly challenged. Many different oral and dental diseases are appearing more and more frequently. For example, the different kinds of fatigue we discussed earlier are corrosion, structural, and vibration [3]. These common phenomena can sometimes lead to oral problems (Figure 6). This article mainly deals with vibration fatigue, which relates to the most basic chewing behavior in our daily life. It does not involve other corrosion or changes in the chemical environment.

Figure 6. Incomplete tooth fracture extending vertically from the occlusal surface [5]

Teeth are known to be brittle, which involves the initiation and growth of cracks. That's why it's hard to detect until it happens. If we want to control the growth of cracks, we need a convenient method to effectively detect potential minor problems in teeth before they develop into irreversible conditions.

Through clinical inspection, a crack may be detected by an aid or an explorer in the color or shadow changing in the fracture area. If there is a subgingival fracture, a localized periodontal defect will be evident [6]. The most common dental aids for detecting cracks are transillumination, magnification, dye penetrants, and radiographs.

Transillumination is the detection method that provides the most information and quickly and graphically represents whether a crack is present. It is based on a law of physics: a beam of light will continue to penetrate through a substance until it meets a space, after which the light beam is reflected. The fracture line separates the tooth's light and dark areas (Figure 7). A dental mirror must be used to evaluate whether a fracture is present. A dental operating microscope is helpful, mainly by turning off the light source and using only magnification along with the dental mirror and transilluminator [7]. Various transilluminators are commercially available, but you could use a fiberoptic handpiece with the bur removed, composite curing light, and other tools as transilluminators.

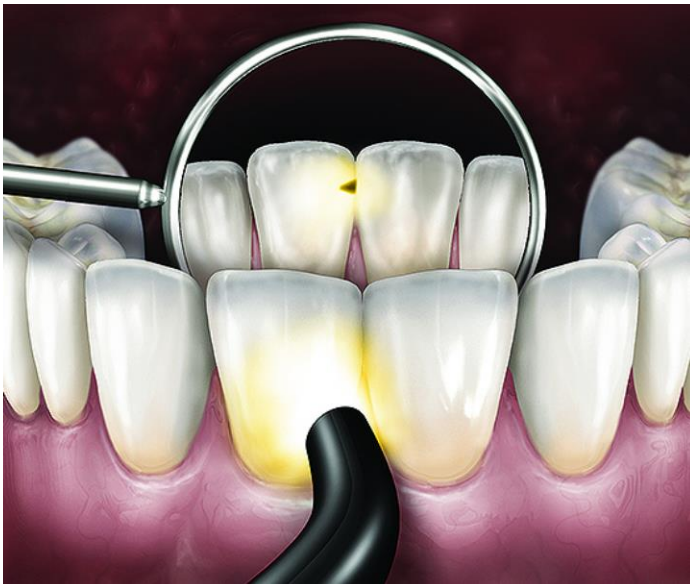


Figure 7. An example of using Transillumination aids

As provided by a clinical microscope, Magnification has been used to locate cracks that are difficult to see with unaided vision [6]. There are two different types of magnification used in the care and treatment of our patients, loupes (glasses) and an operating microscope [9]. Some dentists can combine loupes or safety glasses with tiny LED lights to enhance their ability to spot and treat oral health issues early. The dental operating microscopes magnify the teeth and oral tissues 2-20 times. And it is usually connected to a camera and TV, allowing photographs to be taken and displayed in real-time for patient education or for those who wish to watch their procedures.

Radiography is a technique for generating and recording an x-ray pattern to provide the user with a static image after the termination of the exposure. It is used to diagnose or treat patients by recording images of the body's internal structure to assess the presence or absence of disease, foreign objects, and structural damage or anomaly (Figure 8). During a radiographic procedure, an x-ray beam is passed through the body. A portion of the x-rays is absorbed or scattered by the internal structure [10]. The remaining x-ray pattern is transmitted to a detector so that an image may be recorded for later evaluation.

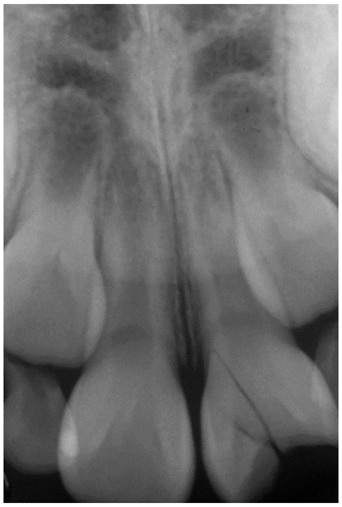


Figure 8. Vertical Root Fracture

1.3 Quantitative Percussion Diagnostics

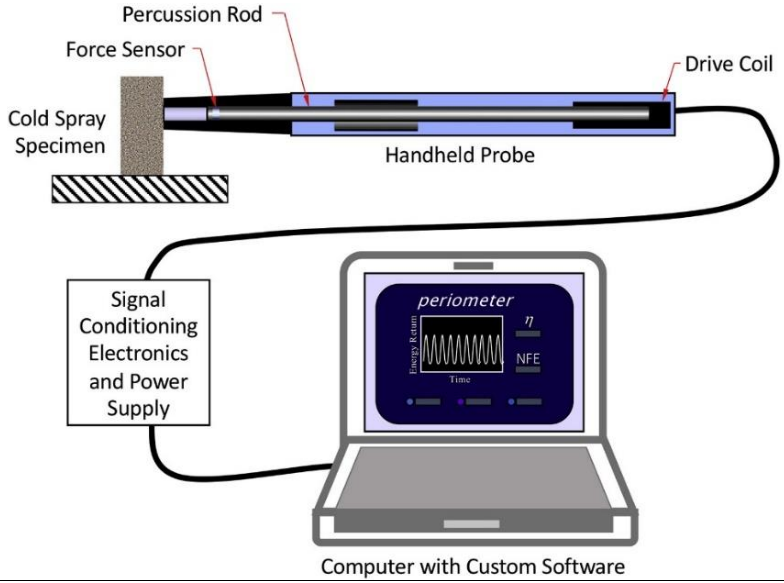
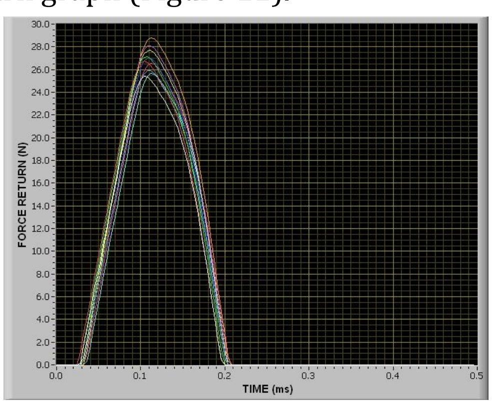


Figure 9. An example of using QPD in dealing with a cold spray specimen [11]

Each method I mentioned above depends on visibility to diagnose the structural defect. But Quantitative percussion diagnostics (QPD) is a non-destructive test based on the mechanical response [15]. It is also an improvement of a method used for decades in dentistry. In dentistry, using the mirror handle is the most common method of percussing teeth to detect sensitivity, mobility, and the auditory sound differential [6]. QPD was developed as a medical device consisting of a computer interfaced with a handheld percussion probe system (Periometer; Perimetrics LLC) that provides data related to the structural stability of the object being tested (Figure 9). In detail, it provides a damping capacity parameter known as the loss coefficient (LC), a plot of the energy returned to the handpiece as a function of time for ten percussions (Figure 10), and a numerical defect indicator known as Normal Fitting Error based on the shape of the data in this energy return graph (Figure 11).



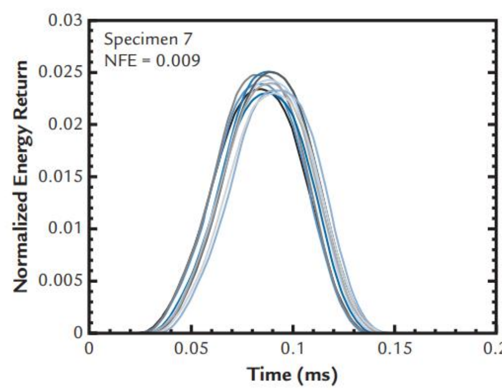


Figure 10. The plot of force return vs. time

Figure 11. The plot of NFE vs. time [6]

The effectiveness of QPD has been proved in other studies [12-14]. Figure 12 is about the comparison between two standard dental diagnostics with QPD. An "X" in the table represents a crack. As for QPD testing, a threshold NFE value of 0.02 for crack detection produced a 98% agreement between the QPD prediction of cracks and the microscopic disassembly verification of the presence of cracks.

Therefore, the findings demonstrate that QPD could detect more fractures in teeth than conventional transillumination, as recorded in the magnified and illuminated destructive disassembly with dye penetrant.

Specimen No.	Transillumination	Microscopic Disassembly	QPD Initial	QPD Final
1	0	X	X	0
2	X	X	X	0
3	0	X	X	X*
4	X	X	X	0
5	0	X	X	0
6	0	X	X	X*
7	0	0	0	0
8	X	X	X	X†
9	X	X	X	0
10	X	X	X	0
11	0	X	X	X*
12	0	X	X	0
13	X	X	X	0
14	X	X	X	0
15	0	X	X	0
16	0	X	X	0
17	0	X	X	0
18	0	X	X	0
19	0	0	X	0
20	0	X	X	0
21	0	X	X	0
22	0	X	X	0
23	X	X	X	0
24	X	X	X	0
25	X	X	X	0
26	X	X	X	0
27	0	0	0	0
28	0	0	0	0
29	0	X	X	0
30	0	X	X	0

Figure 12. Comparison between QPD and other dental aids

Furthermore, the results of the statistical analysis, including the 23 controls with the set of 30 natural teeth, for a total of 53 specimens, showed that 52 of 53 teeth (0.981) were classified into the same category by both QPD and MD. In addition, this analysis indicates that a detection threshold NFE of 0.02 (Figure 13), which was also proved by another study [12-13], for the 53 natural and synthetic posterior teeth achieved 96% specificity [6] and 100% sensitivity [6] for detecting cracks based on a comparison with microscopic disassembly.

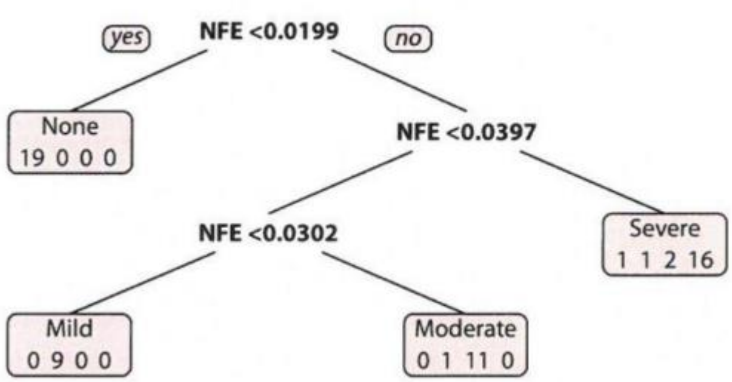


Figure 13. An optimal set of NFE-cutoff [12]

CHAPTER 2: A methodology of printing notched replica tooth

2.1 3D-Printed Notched Replica Tooth

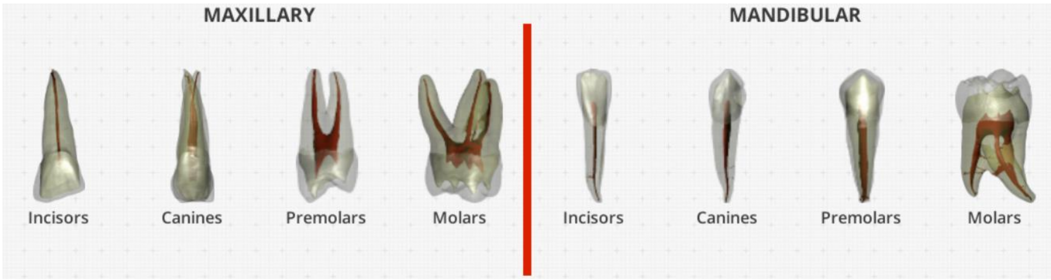


Figure 14. Different types of teeth

As Figure 14 shows above, there are four typical types of teeth, Incisors, Canines, Premolars, and Molars. The incisors are the most visible teeth in the human mouth, as they are the group of teeth in the very front. Each person has eight incisors: four on the bottom and four on the top. Canines are the four sharpers, pointed teeth on each side of the incisors. Canines are similar to incisors in that they help bite and tear food. Premolars, or bicuspids, are located behind the canines and in front of the molars. There are eight premolars, four on the bottom row of teeth and four on the top.

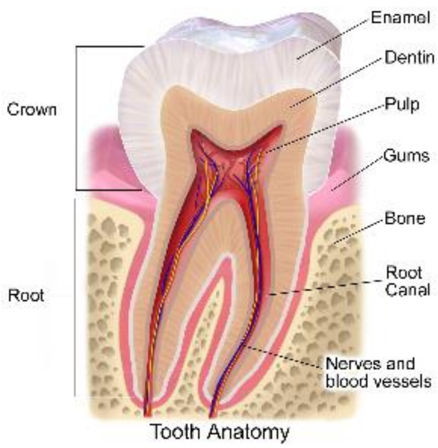


Figure 15. Second molar anatomy

There are also eight molars (four on the bottom and upper row of teeth). Molars are mighty and located in the mouth's farthest back part. The primary purpose of molars is to chew and crush food, which is essential to eating normally. Among these four kinds of teeth, the molar is the most suitable for our design of Gap and Notch. Its outer side is relatively flat, which is convenient for QPD detection because the result in favor of a plane is more accurate than that of a curved surface (Figure 15).

So, after we bought the scanning documents-CAD models derived from hi-res CT scans from eHuman, Inc, we inserted our design, the gap, inside the tooth model. The tooth shown on the left in Figure 16 is the Straight notch design, which we hope we can find an oblique crack. The mechanism of oblique crack formation is discussed in the end.

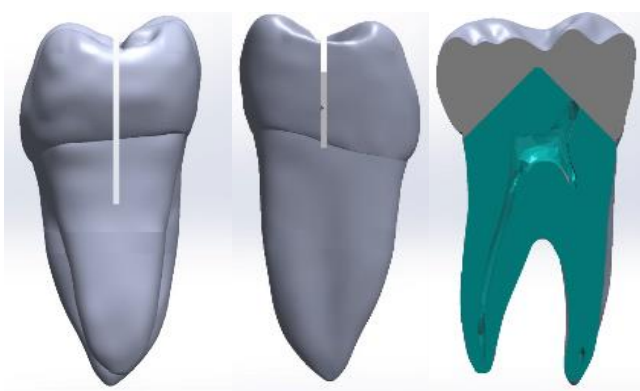


Figure 16. Straight and chevron notch tooth

Because the crack will initiate and propagate at each end of the straight notch and finally meet at the end of the fracture surface. And the one shown on the right is the chevron notch tooth model which the crack is expected to initiate at the tip of the chevron notch and eventually end as a straight crack. In addition, the size of the Gap Space is also important. The gap will close if the space is too small. Besides, a large gap space will lead to uncontrolled growth of cracks, which will deviate from the actual situation of natural teeth. Therefore, the GAP space of 400nm is the best result without artificial processing.

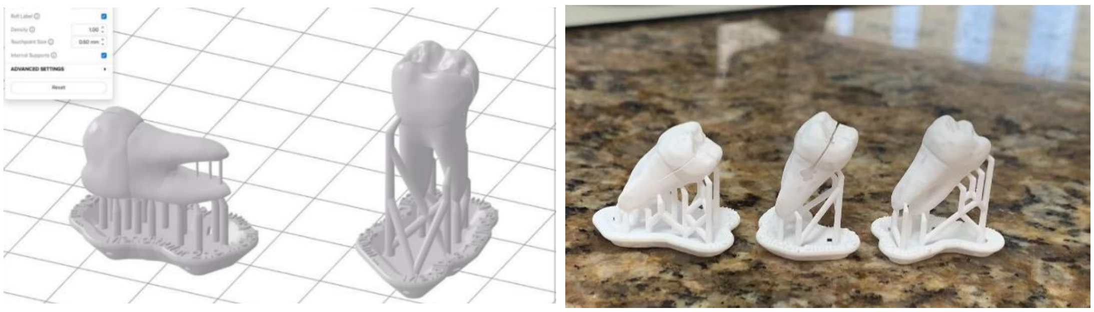


Figure 17. Different ideal positions before and after printing

Then the STL file with our designed model is opened into the printing software from formlabs to nest for printing. The essential nesting procedure is finding the ideal print position (Figure 17). Due to the immature function of the 3D printing instrument, even if the system confirms that there is no error in the software simulation, the printed results are still highly likely to have problems. For example, after the printing, a part of the intact tooth was not closed due to the design of PLUP (Figure 15). As a result, the printed tooth had an NFE value as high as a cracked tooth. This is because the unclosed area inside the replica tooth is pretty tiny, detected as a defect by QPD, and therefore has a high NFE, considered structural instability. In addition, different printing positions will lead to different degrees of gap closure. Once the gap is closed, we cannot manually cut it out with a disk because additional cracks will be generated. Furthermore, other procedures include adding struts, selecting the type of resin (10K rigid, from formlabs), and the layer thickness (50 μm), which need to switch to adaptive printer layers according to the geography of the file. Once the file is sent to the printer (Figure 18) takes about 5-6 hours to print. Then it is placed in an alcohol isopropyl 99% (keystone industries) for 2 minutes with agitation to remove the excess resin. Then it’s transferred into the Form wash (Formlabs) that contains 99% alcohol, and for 30 minutes, it washes off the extra resin with vibrating motions. It is then removed to air dry before placing it into the curing unit Form Cure (Formlabs). It will cure for 60 minutes at 60 Celsius. Once the struts are removed and the teeth are ready to use.

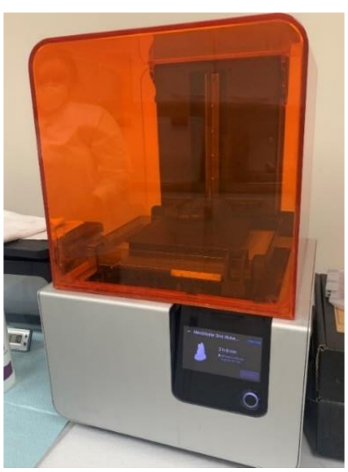
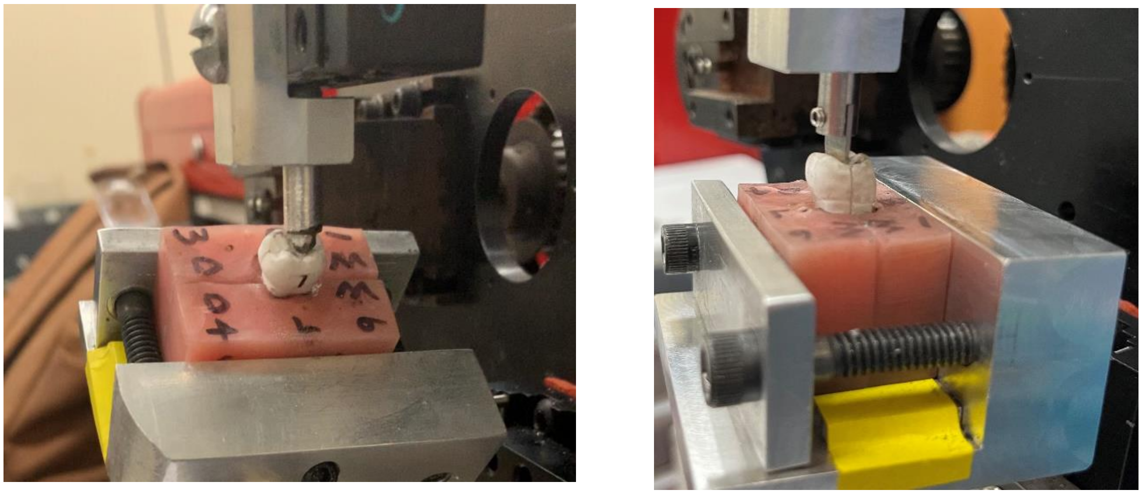


Figure 18. The 3D printer

2.2 Fatigue Crack Preparation



(a) (b)

Figure 19. A picture of pin loading fatigue and wedge loading fatigue

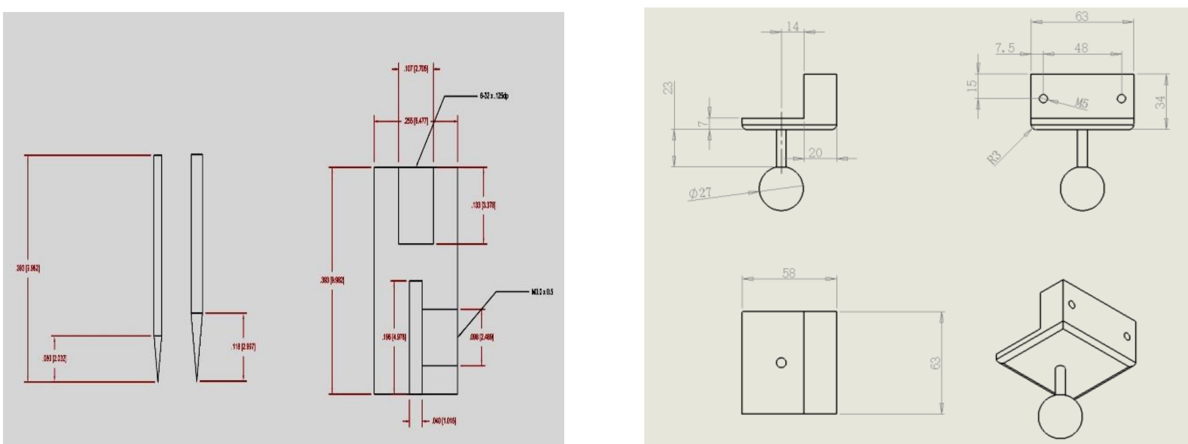


Figure 20. A solid works design of wedge, wedge holder, and clamp shell

Following printing, the replica teeth were loaded in a custom-built fatigue testing machine to produce a sharp crack tip and damage zone at the end of the gap spaces. To adopt two different notches, chevron and straight, we designed a 45-degree pin loading clamp shell (Figure 19, a) with a chevron notch for horizontal fracture and a straight notch for oblique fracture, and another clamp shell (Figure 19, b; Figure 20) to hold the tooth horizontally with wedge loading to cause a vertical fracture.

Before starting to fatigue, we need to choose the perfect sample for the experiment because there is a chance for gap closure and may have some defects on the surface after printing. Then, to obtain a better curve about the increasing NFE value through more fatigue cycles, we used the QPD to test all of the tooth samples that looked good to find the one without a high NFE value due to the defects inside the sample.

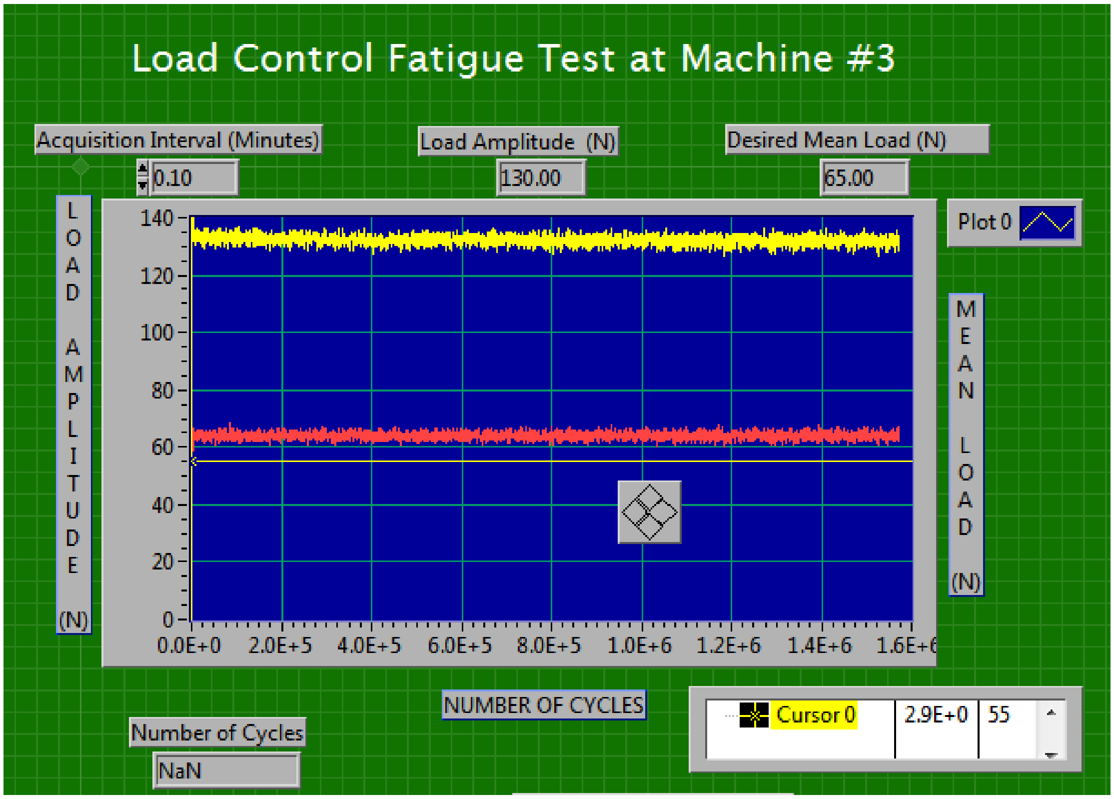


Figure 21. A screenshot of the control interface on the computer

Besides, the machine will start running after we set up the right frequency and load amplitude. Meanwhile, the force measurement curve and the force amplitude will show on the computer screen (Figure 21). The machine is controlled by a computer connected with a motion controller (Figure 22), which can help us automatically move the sample upward to keep the mean force at the same.

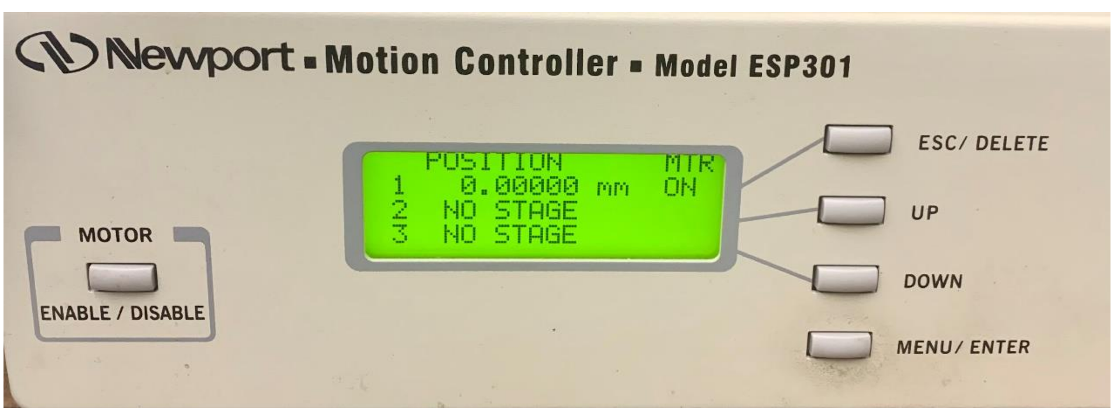


Figure 22. A picture of a motion controller operating system

2.3 Quantitative Percussion Diagnostics Examination

During the QPD test in four different sites marked as 1, 3, 4, and 6 (Figure 23), we not only needed to keep the handheld probe horizontally (Figure 23) not to add additional load during the percussion but also needed to find a flat contact surface to get a more accurate and consistent NFE value.

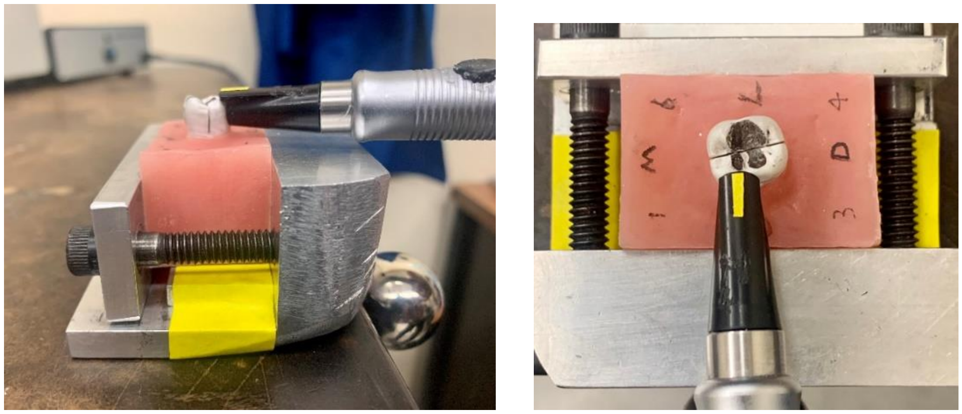


Figure 23. The QPD test after each periodic fatigue cycle

Furthermore, how many periodic fatigue cycles we need to do before we stop each time to do the QPD test is based on the sample's internal structural stability, which takes the NFE reading as an indication. In our initial experiment, all samples will be divided into different ranges according to the initial NFE value, such as 0.01-0.015, 0.015-0.02 (Figure 24), and those greater than 0.02. Then, we ran the machine to fatigue the samples to fracture and write down the corresponding frequency, load amplitude, and cycle number as a reference to obtain an average statistical result. So, we don't waste too many times pausing for QPD in the middle of fatigue when the crack hasn't even been initiated. For example, a vertical 6mm straight notched tooth with a 0.01 NFE value can stand 100N for 1000 cycles to attain 0.02, representing the crack initiation. But it would only stand 70N for 100 thousand cycles, meaning the crack will propagate quickly to fracture once it is initiated. So, we usually decreased the load amplitude and periodic test cycles when the NFE increased significantly to capture the crack propagation.

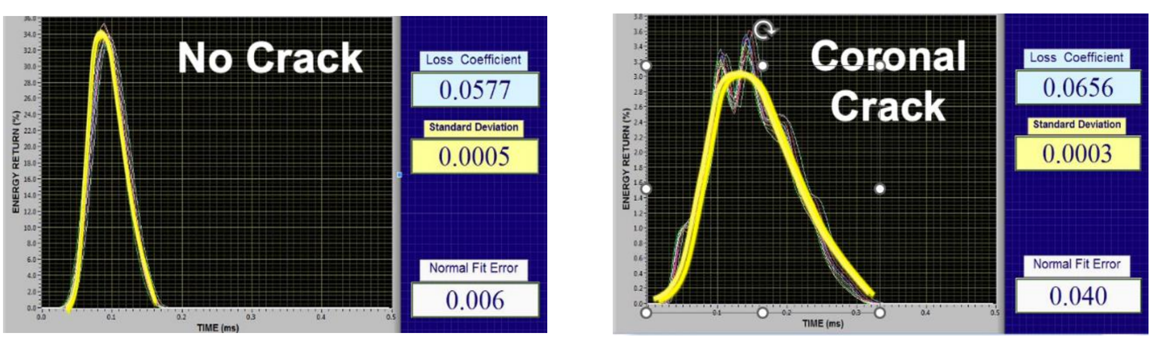
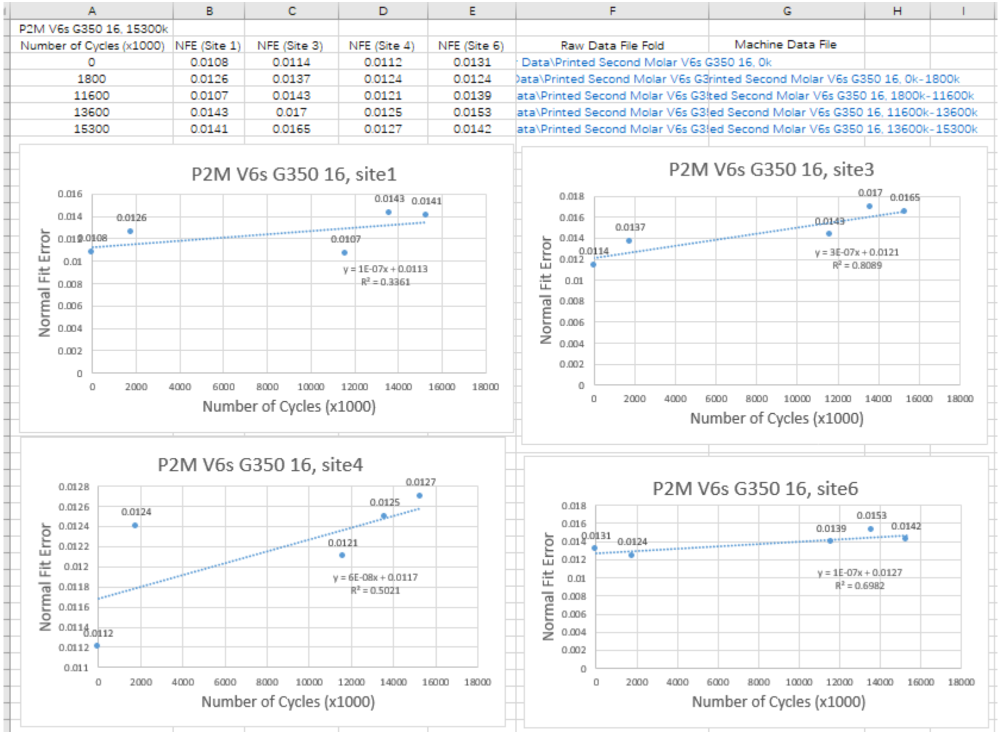


Figure 24. The two types of the representative curve in energy return vs. time

2.4 Results and Discussion



A	B	C	D	E	F	G
P2M V6s G350 16, 15300k						
Number of Cycles (x1000)	NFE (Site 1)	NFE (Site 3)	NFE (Site 4)	NFE (Site 6)	Raw Data File Fold	Machine Data File
0	0.0108	0.0114	0.0112	0.0131	Data\Printed Second Molar V6s G350 16, 0k	
1800	0.0126	0.0137	0.0124	0.0124	Data\Printed Second Molar V6s G3	rinted Second Molar V6s G350 16, 0k-1800k
11600	0.0107	0.0143	0.0121	0.0139	ata\Printed Second Molar V6s G3	ted Second Molar V6s G350 16, 1800k-11600k
13600	0.0143	0.017	0.0125	0.0153	ata\Printed Second Molar V6s G3	ed Second Molar V6s G350 16, 11600k-13600k
15300	0.0141	0.0165	0.0127	0.0142	ata\Printed Second Molar V6s G3	ed Second Molar V6s G350 16, 13600k-15300k

Figure 25. The plot of NFE value vs. fatigue cycles in sites 1, 3, 4, 6

After enough cycles, Figure 25 reveals that the NFE value increased with the fatigue cycles, which means the crack inside the structure is initiated and propagation. The results correspond with the previous study's conclusion[12] about the effectiveness of QPD as an indicator of the level of the structural pathology of teeth shown in Figure 26.

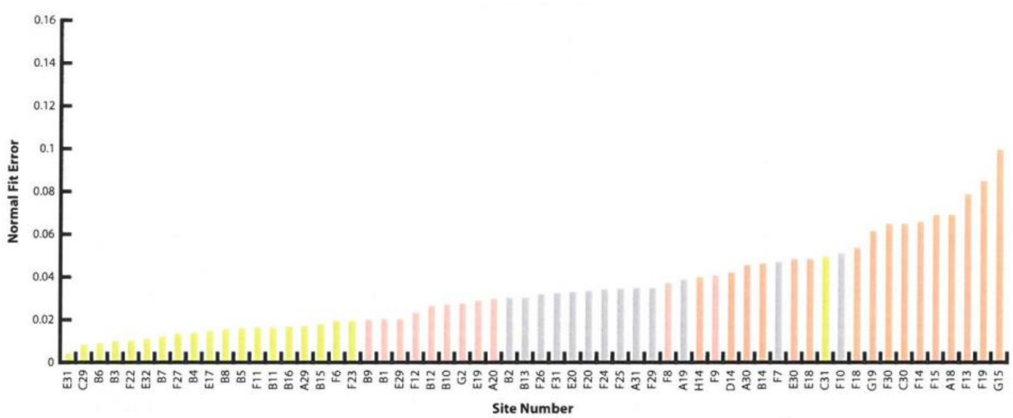
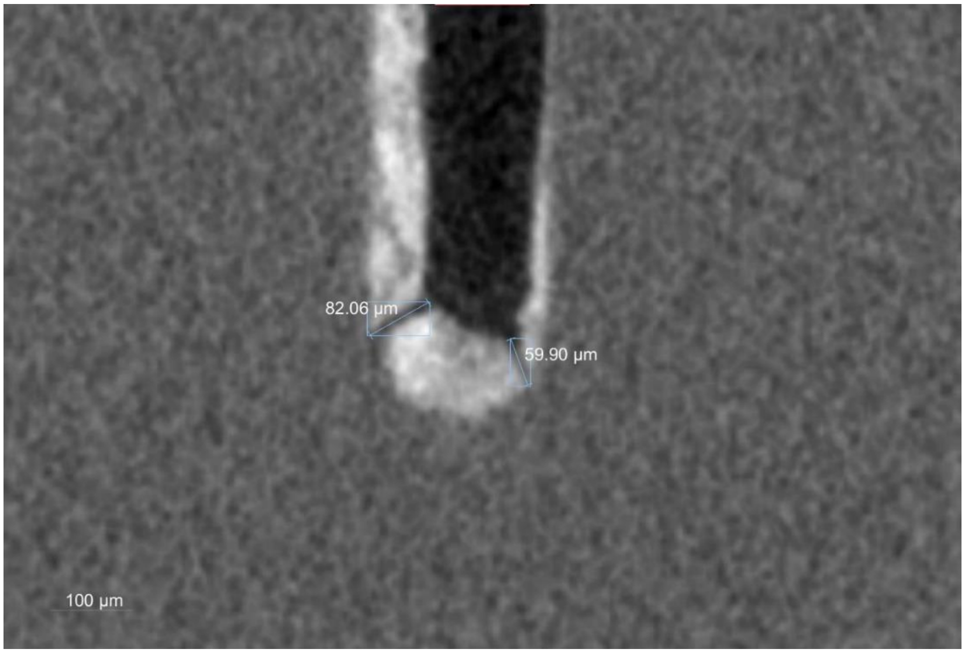


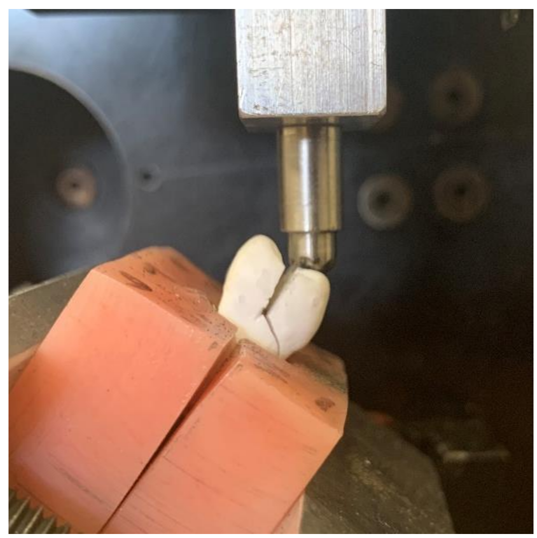
Figure 26. Colored column plotted in ranked order against structural pathology level

Then we used Nano CT(Xradia 410Versa) with a 4X detector, a 4-micron resolution to focus mainly on the notch to reveal the actual crack status.



(a)

(b)



(c)

Figure 27. (a) the Nano CT scanning of sharp crack initiation (b) the 3D model of straight notched replica tooth with an oblique crack after propagation (c) The picture of oblique fracture with pin loading fatigue

First, after we fatigue to the threshold, an NFE value of 0.02[13], the damage zone forms, and the crack starts to grow and open slightly from the notch tip at 45 degrees to the tooth axis, usually around 100 microns(Figure 27, a). Then the crack propagates quickly, continually fatiguing as a sharp crack (Figure 27, b). Eventually, the brittle fracture occurs once the cracks extend to a critical size(Figure 27, c).

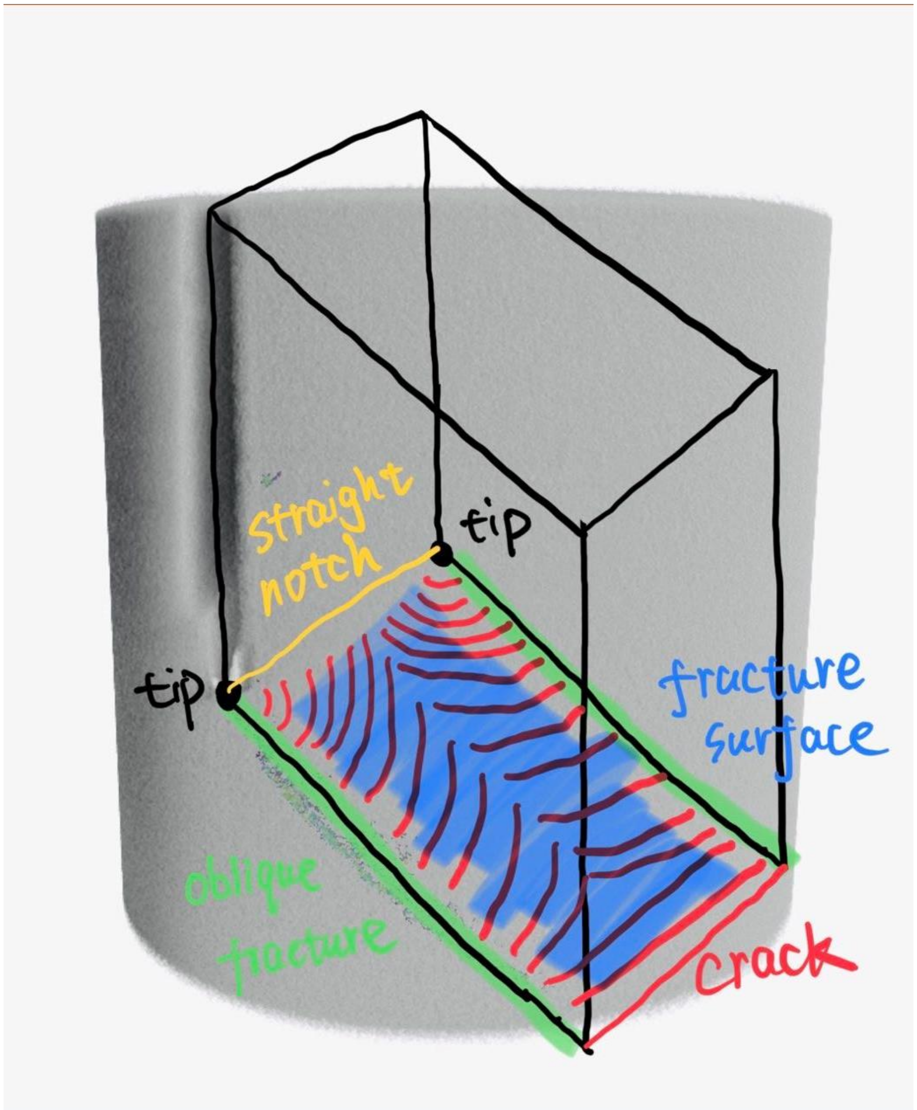


Figure 28. Illustration of fatigue crack growth from a straight notch

Consequently, the mechanism behind the straight notch to oblique fracture is that the fatigue loading generates a short but sharp crack (red line) that extends from the notch tip (black dot) and propagates along 45-degree from the straight notch (yellow line) on the fracture surface (blue region) as the red line shown in Figure 28. And finally, the brittle fracture occurs when the crack extends to a critical size and ends up at the edge of the surface.

CHAPTER 3: Summary and Conclusions

As I mentioned before, the cracked natural tooth is difficult to test or examine in the human mouth. If you want to extract it, the extraction process will affect the tooth itself, leading to more cracks. So, it is difficult for us to know about the internal structural stability of the natural tooth. Not even to mention doing some other tests.
To solve this problem and facilitate future research, I tried to find the scanning of the shape of natural teeth and then use 3D printing technology to make experimental substitutes with replica teeth whose mechanical properties are infinitely close to those of natural teeth. However, there is a significant problem: different orientations and locations of cracks in the teeth. If we only control for the structural stability of the replica teeth, then the results will not be persuasive. According to the most common cracks in the tooth, we designed a gap or a notch vertically in the middle of the replica tooth; the gap space is much broader than the width of the crack. Therefore, the QPD results will remain pretty low as it is an intact structure, even though there is a gap. This design is perfect to avoid the possible risk of imprecise reading of QPD. In the process of fatiguing, the direction of force applied and the shape inside the notch determines the direction of crack growth, which can also help us to simulate the growth of common cracks in natural teeth. Besides, QPD was used both in situ during the fatigue loading and afterward once the cracked replica teeth were mounted in a simulated periodontal ligament, consisting of thin layers of rubber cement and cortical bone fabricated with acrylic resin can essentially simulate the actual tooth situation.

Eventually, we found that fatigue cracks in replica teeth can be produced by building in a notch at a desired location in the tooth, followed by fatigue loading to form a short but sharp crack that extends from the notch tip. Replica teeth containing such a simulated fatigue crack were tested using QPD, and the results were consistent with QPD data for cracked natural teeth.

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