DYNAMIC STRESS CONCENTRATION USING
PHOTOELASTICITY AND A LASER LIGHT SOURCE

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ABSTRACT

Since experimental techniques using dynamic photoelasticity are in general limited by suitably intense monochromatic light sources, it was of primary importance to describe a ruby laser system which would completely remove this particular aspect of the problem. Modulation of the system, in this case by a Kerr cell, provides the necessary control of the light output such that a complete series of results can be obtained by putting together the results of many individual tests recorded on a conventional still camera. In this case the dynamic stress concentration factor in a strut with a symmetrically located circular discontinuity was determined to definitely establish the potential of the system.
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INTRODUCTION

Dynamic photoelasticity has been impeded by the lack of a light source to provide not only a sufficiently intense burst of light having the required photoelastic characteristics but also, a burst of sufficiently short duration to "stop" the phenomenon photographically. These two requirements are generally contradictory in any conventional light source, and a compromise is the practical solution.

The characteristic of the solid state pulsed ruby laser output on the other hand is such that the entire output is 1) parallel
2) monochromatic
3) polarized
4) intense
5) easily modulated

These properties make the ruby laser a natural in its application to dynamic photoelasticity. The scope of this investigation then was primarily two-fold.

(1) It was proposed to set up a modulated ruby laser to demonstrate its capabilities in connection with dynamic photoelasticity.

(2) The potentiality of the system was to be established in studying the effect of a dynamic load on the stress concentration factor in a strut with a symmetrically located circular discontinuity.
MODULATED RUBY LASER SYSTEM

The very nominal output ruby laser used in this investigation, comprising the laser head and 1000 joule power supply is shown schematically in Figure 1. This figure also shows the modulation system comprising a Kerr cell used in conjunction with a 0.5 microsecond bias pulse forming network and its 17.5 kv power supply.

The chromium atoms in the ruby rod are optically "pumped" by an 800 joule flashtube for approximately 2 milliseconds to provide the stimulated ruby laser output which lasts for approximately 1/2 millisecond. This output is made up of randomly oriented "spikes" representing the stimulated output intensity as shown schematically in Figure 2.

This output has the following characteristics:
1) 0.6 joules for the mirrors and cavity shown (not Q spoiled) at room temperature.
2) 6943 Angstrom wavelength (Red).
3) One quarter inch diameter field which is parallel to within one degree.
4) 100% linearly polarized for this 90⁰ ruby.
5) Monochromatic in a spectral bandwidth of 0.1A i.e. three orders of magnitude more monochromatic than the conventional polariscope system.
6) At least 2 orders of magnitude greater in intensity than any Xenon flashtube system.

Because of the randomness of the output and its relatively long duration, it is not too useful for dynamic photoelasticity in this form. In order to explain this randomness it would require a rather lengthy discussion in detail of the physics of stimulated emission which for the novice, is available in textbooks, etc. (1, 2, 3, 4)**

Essentially however, the flashtube excites the chromium atoms in the ruby to a higher energy level and these atoms emit the stimulated output as they return to the ground state. This return to the ground state relaxes the system and more atoms

** Numbers in parentheses pertain to references in the bibliography at the end of the paper
have to be pumped into the excited state again, hence the spiked output.

In order to obtain a controlled output the laser is modulated using, in this case, an electrically activated quarter wave retardation unit, commercially called a Kerr cell. This unit artificially restricts the optical gain in the cavity to prevent lasing until it is required, while the bias pulse forming network prevents lasing after a specified interval. This technique of modulating the optical gain is called Q spoiling since a condition required for this gain is measured by the Q of the optical cavity which is a function of the light wavelength, mirrors and other parameters. As a result of this modulation, the output intensity is further increased by another two orders of magnitude and the total pulse duration is of the order of 0.175 microseconds. This output is also shown schematically in Figure 2. Thus the total increase in intensity over the Xenon flashtube photoelastic light source system is at least four orders of magnitude for this rather modest laser system, as well, the pulse duration may be shortened to as low as 0.01 microseconds without decreasing the output intensity. This pulse is very controllable in terms of duration, intensity and time of its appearance, furthermore, by suitably modulating the Kerr cell bias at say 500 kc/sec then the laser output is also modulated at this same frequency, such that a continuous record of events could be recorded on film. In this investigation, however, only one output spike was used and a sequence of photographs had to be obtained by repeating the experiment and taking a picture at a different instant of time with a conventional still camera.
EXPERIMENTAL ARRANGEMENT

The 1/4 inch thick models, of an epoxy resin, Araldite 6020 with 50 pph Phthalic anhydride hardener, were all 10 inches long and 1.75 inches wide with various sizes of circular discontinuity located symmetrically as shown in Figure 3. The bottom of the models was fixed while the free end was loaded by a 22 caliber projectile, from a compressed air gun, weighing 0.92gms, striking with a velocity 320 ft/sec. The total duration of impact was of the order of 50 microseconds. Two separate triggering systems provided the signals to begin each cycle of firing the laser and operating the Kerr cell. Time was measured from a signal obtained when the projectile struck the top of the model. The block diagram of the experimental apparatus is shown in Figure 4.

STRESS CONCENTRATION FACTOR

The conventional engineering definition of stress concentration factor is the ratio of the maximum stress produced at the critical section over the average stress produced at the same section assuming a uniformly distributed stress distribution. This requires that the load applied to the member be known.

For a transient dynamic loading condition, an accurate determination of the load applied to the member is difficult to obtain hence the stress concentration factor was defined in a manner customary to most analytical procedures. That is, the stress concentration factor K is defined as

\[ K = \frac{\sigma_{\text{maximum}}}{\sigma_{\text{nominal}}} \]

where

\( \sigma_{\text{maximum}} \) is the maximum stress at the critical section
\( \sigma_{\text{nominal}} \) is the stress produced at the section if there were no discontinuity
ASSUMPTIONS

1) A condition of plane stress exists in the model, furthermore at a point on the center line of the model at its mid length a condition of uniaxial stress exists when no discontinuity is present.

2) No buckling of the specimen occurs.

The first assumption implies then, that $\sigma_{\text{maximum}}$ and $\sigma_{\text{nominal}}$ are both directly proportional to their respective fringe order by the familiar expression.

$$\sigma = \left(\frac{2f}{t}\right)n$$

where

$\sigma$ is the normal stress, $f$ is the material fringe constant, $t$ is the model thickness and $n$ is the fringe order. That is: $\sigma_{\text{max}}$ occurs on a free boundary and hence is also a uniaxial state of stress.

Thus, $K = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}} = \frac{n_{\text{max}}}{n_{\text{nom}}}$

The constant $f$ is also rate dependent, however it is further assumed that any effect is negligible when considering the ratio of the two $f$ quantities.

PHOTOGRAPHS

Figure 5 shows a typical development of the fringe pattern for only one of the five models tested. All pictures were recorded with approximately 0.175 microsecond exposure times on polaroid type 47, 3000 ASA film. The spectogram to artificial light for this film shows sensitivity in the range of 3600A to 6500A and yet the laser light at 6943A was quite compatible with this film. For better definition etc. it is more suitable to use the spectroscopic films or even the new polaroid 413 film both of which are sensitive in the infrared region. Figure 6, a typical photograph recorded on 5x7 Kodak Infrared film, shows the resolution obtained.

RESULTS

A test of a model similar to that shown in Figure 3 but having no discontinuity provided the value of $n_{\text{nominal}}$ for the two time intervals after impact considered, namely 100 microseconds and 125 microseconds.

The maximum fringe order was determined by a direct observation of the birefringence photographs for each model at similar times. Each point on the
resulting stress concentration factor curve shown in Figure 7 represents the value obtained from the average of at least three separate tests.

A comparison of results is also shown on Figure 7 including the theoretical static loading stress concentration factors.\textsuperscript{6,7}

**DISCUSSION OF RESULTS**

It must first be noted that the propagating fringes shown in Figure 5 (before the discontinuity) are not straight as assumed in the uniaxial stress assumption. Evidently plane sections do not remain plane and a two dimensional state of stress is developed. Even though the applied load was only distributed over an area approximately 1/4" by 1/4" in size, it was expected that at large distances from the point of application, a relatively straight fringe would exist. Apparently the loading at the center of impact includes many more high frequency impulses which are damped out in a short distance hence contributing to the nature of the propagating fringes.

Figure 7 would indicate that the stress concentration factor as determined using this particular arrangement and model material is linearly related to the a/b ratio and as well dependent upon the time after impact. This latter observation was unexpected since theoretically\textsuperscript{8}, the stress would depend on the impulse wavelength (approximately constant) and Poisson’s ratio. However, the trend toward decreasing stress concentration as the ratio a/b increases, comparing the dynamic and static values is obvious and reasonable. It is reasoned that as the hole becomes very large, the impinging wave tends to see it as a flat boundary thus reflecting the wave normally and leaving the boundary stress free.

It has also been shown theoretically\textsuperscript{8,9} for some dynamic problems that in order to get a significant dynamic effect the stress wave pulse must be long with respect to the model thickness and short with respect to the model length. For a stress wave pulse duration of some 50 microseconds and a propagating velocity of 5300 ft/sec\textsuperscript{10} this distance is 3.17 inches compared to the 1/4 inch thickness and 10 inch length.

Although the dependency of the stress concentration factor on the time after impact was noted, it was not extensively explored, nor was the effect of the changing impact velocity of the pellet, or other such variables.
CONCLUSION

1. Even though the energy output of this laser system was only 0.05% of the largest systems available to date, it is felt that its potentiality in dynamic photoelasticity has been demonstrated. The high intensity, megawatt range, provided sufficient intensity to take pictures on film not particularly sensitive to this red wavelength.

If the light field is in fact parallel then the image at the camera should be in focus everywhere, the position of the film plane then only determining the size of the image. This is not precisely true of this laser system however there is a very generous region where the image is in focus at all positions.

Modulating the laser output using the Kerr cell provides a control of the output pulse quite reliably to within 2 microseconds such that the birefringence photographs appear very consistent. Current experiments in modulating the output in an attempt to gain frequencies of 100 kc/sec to 500 kc/sec would permit a continuous record of events by recording on a high speed rotating mirror camera. The tremendous advantage in modulating the light source itself occurs in the simplicity of the camera since it would require no shuttering action but only a rotating mirror to separate the images on the film strip.

The choice of the Kerr cell to provide the required modulation is rather undesirable since the quarter wave bias is 17.5 kv. A more reasonable system would employ a Pockel's cell whose quarter wave bias is an order of magnitude less, hence the voltage modulation would be much more feasible.

2. For this investigation the stress concentration factors obtained dynamically do not experience the very large values characteristic of the static loading condition for large a/b ratios. Further the dynamic stress concentration factor varies almost linearly with the ratio a/b, as well, the stress concentration factor using this epoxy, is evidently dependent on the time interval after impact.

3. It is estimated that the experimental errors experience were of the order of 15%. 

BIBLIOGRAPHY


FIGURE 1 SCHEMATIC OF THE LASER AND MODULATION SYSTEM

FIGURE 2 TYPICAL TIME TRACE OF THE UNMODULATED AND MODULATED LASER OUTPUT
MODEL THICKNESS 1/4"

\[ 2a = 7/16", 11/16", 7/8", 1 1/16", 1 5/16" \]

FIGURE 3 MODEL DIMENSIONS

FIGURE 4 BLOCK DIAGRAM OF THE EXPERIMENTAL SETUP
FIGURE 5
TYPICAL FRINGE DEVELOPMENT $a/b = 0.607$
NUMBER INDICATES $\mu$SEC. AFTER IMPACT
0.175 μsec. exposure
6 1/2 X neutral density filter

FIGURE 6
TYPICAL FRINGE PHOTOGRAPH ON
5X7 INFRARED FILM
FIGURE 7 STRESS CONCENTRATION FACTOR 
vs RELATIVE SIZE OF DISCONTINUITY