FROM THE ARCHIVES

Report on Physical Effects of the Sonic Boom (1968)

Pages
21

Size
8.5 x 10

ISBN
0309300770

Subcommittee on Physical Effects; Committee on SST-Sonic Boom; National Research Council

Committee on SST-Sonic Boom

Subcommittee on Physical Effects

Report on

Physical Effects of the Sonic Boom

February 1968

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19 February 1968

Dr. John R. Dunning, Chairman
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National Academy of Sciences
2101 Constitution Avenue, N. W.
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Dear Dr. Dunning:

At the 20 February 1967 meeting of the Committee, the Subcommittee on Physical Effects was requested to examine the current status of matters relating to "structural" response to sonic booms and to report what further research should be conducted.

Transmitted herewith is the requested report; its transmittal has been delayed in order that the Subcommittee might review the final report on the physical effects aspects of the Edwards AFB program and preliminary data on alleged damage resulting from the Department of the Air Force operational-suitability testing of the SR-71.

Overall, the Subcommittee is principally concerned about (1) the need for greater accuracy in the statistical description of the variations of boom signatures and physical responses; (2) the implications of the true statistical descriptions of the "natural" variations of boom signatures from the presently accepted "computed" boom signatures; (3) the lack of attention being given to the notions of incipient and progressive damage of materials; and (4) the lack of progress being made in the development of simulator capability inasmuch as continued overflight test programs can result in data which, at best, only partially close the gap in knowledge.

Accordingly, the Subcommittee recommends that the research outlined below (in descending order of priority) be undertaken promptly and pursued vigorously:

1. Design, construction, and operation of two types of simulators

2. Repetitive testing in simulators of a wide range of damage-susceptible materials and assemblies

3. Static and dynamic testing of glass and glass systems

4. Acceleration and expansion of ESSA's sonic boom studies

5. Census, by sample survey, of window panes in selected cities

6. Evaluation of environmental parameters of material and building responses to natural phenomena

7. Theoretical study of critical earth structures

8. Interdisciplinary group study of legal-structural considerations

9. Study of means of accomplishing a national boom monitoring network.

Sincerely,

Everett F. Cox

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Subcommittee on Physical Effects

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I. INTRODUCTION

Purpose and Scope

At the request of the National Academy of Sciences' Committee on SST-Sonic Boom, the Subcommittee on Physical Effects has undertaken to examine the current status of matters relating to "structural" response to sonic booms and to report what further research should be conducted.

"People" response to sonic booms or noise is currently considered an important factor which may determine the degree to which commercial over-land supersonic flights will be made. For the purposes of this report, it is assumed that such flights will be made.

Conduct of Study

Work on this study was initiated by reviewing data available in draft and final reports of prior Federal Aviation Agency-, National Aeronautics and Space Administration-, and National Sonic Boom Evaluation Office-sponsored sonic boom tests, including the recently concluded Edwards AFB program. Other related material such as data available from the on-going Department of the Air Force operational-suitability testing of the SR-71 was also reviewed. Additionally, several Subcommittee meetings were held to consider carefully many facets of the "structural" response problem, including shock diffraction, meteorology, and topography and ground reflection of shock waves.

Organization of Report

This report comprises three sections: This INTRODUCTION; DISCUSSION of the basis of the physical effects research program and of its several elements; CONCLUSIONS AND RECOMMENDATIONS.

II. DISCUSSION

Program Basis

The assumption that, at some point in time, there will be commercial supersonic flights over land areas immediately engenders two classes of "structural" response questions, viz.,

1. Given sonic boom characteristics having acceptable "people" response qualities, what kinds and amounts, if any, of physical damage should be anticipated?

2. What data are necessary to enable equitable compensation for such damage as might be induced by sonic booms?

Understanding of material responses to transient loadings is not complete and may never be, but a higher level of understanding is attainable and is required before realistic answers to these questions can and need be given finally.

Because the probability of material damage being caused by a sonic boom generated by an aircraft operating in a safe, normal manner is very small, our current inability to provide realistic answers reflects (1) our incapability to describe, with sufficient statistical accuracy, the response characteristics, extent of usage, and the "normal" environment of building materials and assemblies; and (2) our incapability to comprehend, also with sufficient statistical accuracy, the complex loadings imposed on building assemblies by sonic-boom pressure perturbations as they have been observed after transmission through "natural" atmospheres. Our inability further reflects lack of attention heretofore given to that aspect of the materials response problem which involves notions of incipient and progressive failures.

In sections that follow, research and other actions which seek to improve our abilities are recommended and discussed in some detail. It is urged that each item be undertaken promptly and pursued vigorously.

Simulators and Repetitive Testing

Simulator Development. The use of supersonic aircraft in overflight test programs is one way of acquiring sonic boom field test data on the nature of physical effects of sonic booms. However, due to the unpredictable nature of atmospheric effects at any given point in time and space, it may be impossible to conduct thoroughly controlled overflight experiments yielding reliable and reproducible data for detailed comparison and analysis.

On the other hand, if there existed laboratory-type test equipment which simulated sonic boom forces in a controlled, reproducible manner, then test programs utilizing such equipment would provide scientifically valuable data concerning the physical effects of booms on materials and systems of construction. The argument for developing such equipment is strengthened by the fact that most boom amplitudes are smaller than are ordinarily considered to be destructive, and hence large numbers of repetitive loadings and samples are needed in order to generate extreme-value statistics required for application to the boom economic consequences question. Thus, if the data developing capacity of a simulator were on the order of 60 waves per hour, one-day's continuous operation would simulate a year's exposure to three booms per day.

As indicated by the Langley Low Frequency Noise Facility, it is feasible to construct boom simulators that are useful in evaluating the effects of sonic boom type loadings on building materials and assemblies. The use of the Langley facility for evaluating physical effects should continue, but at least two additional types of simulators should be built.

The first type should be used to evaluate materials in assemblages up to 8 ft. by 8 ft. This development would provide basic data for use in the subsequent designing of a simulator for testing larger assemblages. In all likelihood, the initial unit could be a room having one end-wall or section which could be activated like a piston in a cylinder. The activating mechanism for the end-wall would desirably be adjustable so that a range of "N" wave characteristics, such as varied positive and negative pressures, pulse duration, and rate of pressure rise and decay, can be simulated.

A second type of simulator should be designed to test and evaluate whole structures, on the order of 20 ft. x 20 ft. x 20 ft. The same basic "cylinder-piston" technique might be applicable to this larger chamber, but the need for the fidelity with which a precise N-wave must be produced is not now clear, and thus it is not now known whether a simple-piston, compressed-air pulse will be satisfactory or whether a blast-activated load is needed.

Considerable information concerning "N" waves of various aircraft, as propagated through various meteorological strata, is already available. From what is already known, it appears that the range of operation for the simulator should allow for generating "N" waves with the following range of conditions:

Peak-to-peak amplitude:	0.5 - 10 psf
N-wave duration:	0.1 - 0.5 second
Rise time preferred:	5 - 100 msec.
Rise time acceptable:	10 - 100 msec. (cost will determine)

Since it appears that the measurable response of many building materials and assemblages to impulse loadings may be independent of small variations in rise time of the pulse, it may be possible to relax the requirement that the simulator produce near-instantaneous rise times, at least for many types of specimen tests. And since it appears that the measurable response of assemblages having natural periods greater than the natural period of the applied pulse is independent of the details of the pulse profile and is mainly determined by impulse, the requirement that the simulator produce truly N-shaped waves may also be relaxed.

Higher fidelity simulation may only be necessary for some structural systems. The re uirement will only be completely defined after a thorough analysis which should be immediately undertaken, and after a period of test experience in the small simulator. Additionally, it may be desirable to generate variations from simple N-waves in order to simulate possible atmospheric and diffractive perturbations.

The test equipment should also be capable of conducting tests at temperatures ranging from $-65^{\circ}F$ to $+150^{\circ}F$ in the small simulator in order to cover temperature extremes encountered in the United States; temperatures ranging from $0^{\circ}F$ to $100^{\circ}F$ in the larger simulator will be acceptable. This will permit the evaluation of simulated sonic boom overpressures on materials, systems and structures over a wide range of environmental conditions.

For the simulator study effort, including the preliminary analysis, it is estimated that the order of $150,000 per year (exclusive of simulator costs) for two years should be appropriated.

Damage Susceptible Materials. The characteristics of certain materials and structural systems are such that they are susceptible to damage from small pulse-loads of the sonic boom type. The materials and/or systems listed below, as potential problem areas, should be subjected to a simulated sonic boom testing program, with emphasis on repetitive boom-type loadings, to:

a. Improve probability definition in extreme value statistics
b. Indicate needed improvements in manufacture, handling, and installation of building materials and systems
c. Predict possible incipient failures due to aging
d. Estimate damage costs from repetitive SST-boom applications.

Where aging and exposure to the elements contribute to the changing of properties of materials, the test program should include accelerated exposure environments prior to loading.

Potentially critical materials and assemblies to be tested, in order of criticalness, are:

1. Glass, moldings, and mountings. See page 6 for detailed discussion.

2. Plaster, including (a) unset basecoat plaster on masonry, gypsum lath, metal lath, and concrete; (b) finish coat plaster newly applied over basecoats or other bases; (c) plaster applied to "poor" bonding mediums such as asphalt coatings on concrete or masonry; (d) wet cement and stucco on all surfaces; (e) dried and undried wall board joint (tape) systems; and (f) newly applied wall board using adhesives to attach the board to frame or other base.

3. Masonry materials and systems, including (a) cementing materials and brick, interior and exterior tile, concrete block, and stone; and (b) interior stone facings set in plaster of Paris.

4. Organic and inorganic adhesives, including acoustical tile adhered to all substrates, particularly concrete.

5. Roofing materials and systems, including (a) built-up roofing, particularly at low temperatures and with embrittlement of asphalt and felts; (b) long-span structural systems including grouting, adjacent components, and membranes; and (c) flashing.

6. Plastic materials, particularly extruded polyvinyl-chloride panels and similar thermoplastic building materials at low temperatures.

7. Wall paper, particularly old.

8. Incipient failure of the following particular materials and assemblies:

    a. Deteriorated caulking, adhesive gaskets, and sealants.
    b. Deteriorated fasteners for building materials and systems.
    c. Plaster with weakened bond.
    d. Deteriorated brick courses, particularly at roof lines.
    e. Cornices and copings in weakened conditions.
    f. Lay-in acoustical ceiling panels.
    g. Lay-in lighting units.
    h. Incipient nail popping.
    i. Partitions under thin flat-slabs subject to creep.
    j. Partitions framed into exposed structural columns.

There is evidence that the materials and assemblages included in the foregoing list may be susceptible to rapid deterioration with repeated stressing under natural environmental conditions. Because this repeated stressing may be at a slow rate, the progressive deterioration and fracture of the materials may not be detected readily. Such developments may very well not be, in any way, related to sonic booms. Environmental conditions, e.g., sub-zero temperatures, may be found to be most critical in connection with the effect of repeated stressing of certain materials.

The importance of this investigation must be emphasized; the establishment of failure criteria is virtually impossible without a controlled test program. Future claims of damage to materials in the foregoing list will be difficult to evaluate unless definitive statistical information is developed.

Some of the above materials could be tested for cumulative effects from small loadings by simply reproducing the deflections which have already been recorded in overflight tests. Application of a few thousand cycles of small distributed loads could answer some questions for plaster or drywall panels exposed to such repetitive loads.

The initial phase of this study should be concerned with identifying problem areas more deliberatively than was possible for this report, and should include some laboratory tests during the development of the boom simulators. This would provide evidence of damage potential which would aid in the planning of the test program for the boom simulator. Thus, it is recommended that this research be undertaken concurrently with the development of the sonic boom simulators. For the preliminary materials studies, including the simulator test studies, it is estimated that an additional $150,000 per year for two years should be appropriated.

Glass Problems

Laboratory Tests. A majority of claims submitted and damages paid for booms and explosions are for window glass breakage, and yet there are only limited static test data in regard to the strengths and responses of glass. The amount of dynamic test data available is much less.

There is need for further tests of glass resistance to over-pressures. Data in manufacturers' technical reports tend to be inadequate and misleading for analysis of small-probability boom damages. Supporting test data have been reviewed in detail, and, although it is possible to correct the gross difficulty by use of different statistical models, such as log-normal or Weibull distributions, there are test sampling problems which require further laboratory work.

Test samples should be in the range of a thousand specimens for each thickness to approach the extremely low damage probability levels associated with sonic booms. Some tests should also be made on large specimens to ascertain better whether net boom loading on glass is the dominant parameter. Tests should also be made on typical framed panes to establish better whether caulking, moulding, installation or pane defect is more important. Additional more-uniform loading tests should be used to make sure that results are valid for boom loading, and tests should be made on panes from several glass producers. It would also be very useful, and therefore essential, to test samples which have been installed for a few years, if they could reasonably be recovered from buildings being razed.

Quite apart from the foregoing verification of existing test data, there is need for further theoretical research into glass failure. There are probably some "flaw mechanisms" involved in glass failures, and whether or not this is amenable to quality control is not known. How much is attributable to handling is not known. Depending on the mechanism involved, the probability distribution for glass breakage can not be specified at this time.

There is need for definition of pane loading probabilities based on the statistics of reflections in urban environments. This would require consideration of such statistical variables as building size, spacing, height, and boom wave incident angles in both azimuth and elevation in order to determine the probability and distribution of constructive interference and reflection.

Each of these three areas of study might appropriately be undertaken by engineering colleges. The first could be the most expensive if pursued in great detail, but a man-year effort plus specimen and apparatus costs would appreciably advance the state of knowledge about glass and would materially improve boom damage predictions. Theoretical research into failures should be supported to the extent of about a man-year of effort. The calculations in reflection statistics should only require a short-term effort by a "competent geometer."

Survey. The degree of utilization of glass in building construction and the fact that glass damage thus far represents the largest share of boom damage now warrant better appraisal of the true extent of glass usage. Thus, there is need for window pane census data.

Sample data should be collected in regard to the number of panes that exist in each of several glass-size categories in several of the metropolitan areas overflown during the 1 July - 1 November 1967, Department of the Air Force operational-suitability testing of the SR-71, e.g., in Albuquerque, Chicago, Dallas-Fort Worth, and Denver. Similar information should be obtained for Oklahoma City, where previous boom studies have been made; for Boston, San Francisco, and Phoenix, to represent climatic variations; for

Jacksonville, Florida, and Portland, Oregon, to give climatic spread on smaller cities; and for perhaps six small cities of 15,000 to 25,000 population in various states, to check effect of city size. These census data should then be correlated with data available from the analysis of the Medina explosion near San Antonio, with the wall aperture data available from the Office of Civil Defense, and with the building inventory data available from Sanborn maps of urban areas in order to postulate the glass pane population now existing.

Propagation Theory

Signature Study. The Subcommittee on Research of the Committee on SST-Sonic Boom has recently covered the subject of propagation in some detail in Report on Generation and Propagation of Sonic Boom, dated October 1967. The Subcommittee on Physical Effects wishes to emphasize the fact that the probability of serious material damage being caused by a sonic boom generated by an aircraft operating in a safe, normal manner is very small.

Logic suggests that measured characteristics of all sonic booms are not normally distributed and have some degree of truncated upper and lower bounds, and that such bounded distributions have different skew characteristics for different aircraft, flight conditions, over-pressures, periods, climates, and geographic locations.

The recent efforts of the Environmental Science Services Administration (ESSA) to use Edwards AFB test program data to demonstrate the effects of atmospheric perturbations on sonic boom signatures recorded at ground-level are highly valuable, even though these efforts are but a start. (Early work by ESSA at Edwards AFB was necessarily meteorologically limited and exploratory in nature.) On a priority basis, ESSA should not only continue its studies, particularly the boundary layer turbulence study, but these studies should be expanded to include analysis of atmospheric and sonic boom data recorded at locations having different meteorological and topographical characteristics; urban centers should definitely be included.

Environmental Parameters. It is possible that the responses of building assemblies to lightning, resulting in a cylindrical shock wave that causes thunder, and wind gusts may be in some ways comparable to the responses to sonic booms. Thus, study of loading amplitudes from these natural events, the frequency of occurrence, and the resulting damage or deterioration rates might allow subsequent comparative evaluation of repetitive boom loads and the acceleration of aging caused by supersonic aircraft operations.

There are few pressure-time recordings of thunder. To shorten the statistical gathering period, more recordings should be obtained, using standard microphone boom-recording equipment, at locations where numerous lightning strikes are known to occur. Additionally, from cloud-physics studies, the national climatology of strike occurrences should be estimated to yield the distribution of lightning-booms (thunder) and amplitudes expected to strike typical structures. Comparison with supersonic aircraft boom predictions will then show how much more, or less, than such ambient damage occurrence can be expected.

Currently, for structural wind loading calculations, use is made of weather statistics, which were obtained well above ground-level in the open, usually at airports. The distribution of gust loads actually experienced in a city residential or high rise building environment is known to be different. Detailed wind recordings should be made in several urban areas and close to buildings so that truly effective gust distributions can be compared with the large body of "airport-type" wind data. From these, an estimate of window and plaster damages caused by storm wind gusts can be produced. The estimates will be useful in making realistic appraisals of the natural lifetime for structures, windows, and plaster walls claimed damaged by booms.

These tasks should be accomplished in conjunction with the existing ESSA weather observation program. In this way, each project could benefit from the others. This small effort could be spread over a two-year data collection period.

Earth Structures

There are indications that there are some earth structures that may be susceptible to failure under dynamic loadings such as sonic booms, namely (a) slopes, either cuts or fills, which have critical or small factors of safety and (b) foundations on unstable sand strata or "quick" clays.

The most critical condition for slopes occurs when the slopes are saturated such that relatively small superimposed pore pressures, such as from sonic booms, may reduce frictional resistance sufficiently to diminish factors of safety to less than one. An analytical study should be undertaken to determine the pore pressures required to cause failure of slopes known to have low factors of safety. Experts in soil mechanics should be able to identify readily critical structures for analysis purposes.

Although of lower priority, but nevertheless a potentially dangerous situation of considerable concern, are the foundations with soils that could become unstable under certain conditions. There are known examples of failures of foundations under structures where either sand strata or "quick" clays become unstable under certain conditions as a result of loadings. For example, a large structure above ground, may receive either an impact loading from a wind gust or sudden pressure wave or from an earth tremor which may, in turn, be transmitted to an unstable strata and thus trigger the material into instability. Fortunately, such conditions can be treated theoretically. By analyzing existing structures, soil properties and configurations, it would be possible to estimate the potential for such failures under dynamic loads. Further, it may be possible with a boom simulator to evaluate and demonstrate failures in such soil structures.

Both types of studies require the collection of pertinent information and then the development of analyses to determine the magnitude of over-pressure required to induce failure. A small initial exploratory study would result in much valuable information on this problem and should indicate the degree of potential danger.

Some natural formations, notably those at a point of incipient failure, may be potentially susceptible to sonic boom damage. However, inasmuch as seismic signals and shock loadings induced by sonic booms have been demonstrated to be measurably less than those resulting from naturally occurring phenomena, such failures would occur in any event the next time a comparable stress was induced by natural forces.

Legal Considerations

There are two legal-structural problems which warrant attention to avoid establishment of inequitable legal precedents.

First, there exists a need for criteria for adjudication of claims for damage not attributable to a single cause, but for damage which is a logical result of progressive failure of a structural material from repetitive loading.

Second, there exists a need for criteria for adjudication of claims for damage resulting from incipient failures which would have occurred the next time natural phenomena (wind, thunder, earth motion, etc.) produced comparable stresses.

Rather than a research effort, it is suggested that an interdisciplinary group be appointed to recommend structural criteria and compatible legal standards. Such a group might be appointed from appropriate professional associations such as the American Society of Civil Engineers and the American Bar Association.

Noise Recorders

In the future, should commercial supersonic flights be scheduled over populated areas, as opposed to over-ocean flights only, some type of boom-monitoring system may be needed. This may be required (a) to verify occurrence of allegedly damaging booms, (b) to define boom-swath path and the particular source of damaging booms, and (c) to determine why these excessive booms occurred--whether they were pilot-caused (with or without intent), or if they resulted only from "natural" causes such as atmospheric focusing, turbulence, or multiple reflections, like those in the vicinity of a building group.

It is recommended that several competent companies specializing in instrument-data-recording-and-retrieval systems be contracted to study means of accomplishing a national recording network for monitoring sonic booms. (An estimate of each study contract is $50,000, with time duration one year.) The costs involved in a nationwide installation could then be calculated prior to the initiation of trans-continental commercial supersonic flights.

III. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. Current understanding of sonic boom loadings and of the responses of building materials and assemblies to such loadings is insufficient to assess accurately what kinds and amounts of physical damage will occur. The probability of material damage being caused by sonic booms generated by aircraft operating supersonically in a safe, normal manner is very small.

   a. The variability of individual boom signature parameters under different climatic and geographic conditions and for different types of aircraft and aircraft operations can not now be described with any great degree of statistical significance. Carefully conceived, properly instrumented test programs can improve this description capability: see Report on Generation and Propagation of Sonic Booms, dated October 1967.

   b. Currently, it is only possible to describe generally the nature of potential-material-and-building assembly responses, expressed as functions of sonic boom signatures. Present description capabilities can only "explain" why wide-spread damage does not occur--it can not explain "damage" that either is alleged or does occur. Continued over-flight test programs can not materially improve this description capability.

   c. Currently, it is not possible to describe the effects of "normal" environment (such as thunder, wind gusts, and street traffic) which contribute to the repetitive, vibratory loading of buildings and structures and to which the sonic boom is additive.

2. A wide variety of materials and assemblies is potentially susceptible to damage even as a result of wind gusts or sudden pressure waves or earth tremors. Many of these potentially susceptible items are more apt to be damaged by repetitive loadings (say, on the order of several thousand) in combination with the changing of physical properties of the materials as a result of aging and environmental exposure rather than by a single exposure. The most critical materials and assemblies which need to be explored are listed on pages 5 and 6.

3. Currently, the majority of sonic boom damage claims and the largest dollar cost result from window glass breakage.

4. Thus far, few sonic boom damage claims have involved earth structures (or other materials stored at their normal angle of repose), foundations, or natural formations, but if such damage does occur, the effect and the cost can be troublesome.

5. With the advent of commercial supersonic flights over populated areas, some form of nation-wide boom-monitoring system may be required.

6. Two legal-structural problems warrant early attention to avoid establishment of inequitable legal precedents.

Recommendations

1. At least two types of sonic boom simulators for testing on the order of eight-foot square panels of typical construction materials and twenty-foot on a side cubic assemblies should be immediately designed and constructed.

2. A physical response research program, comprising the following elements in descending order of importance, should be immediately undertaken and vigorously pursued:

   a. Repetitive tests in simulators of a wide range of damage susceptible materials and assemblies listed on pages 5 and 6.
   b. Static and dynamic laboratory tests of commonly used glass and glass systems.
   c. Acceleration and expansion of ESSA's sonic boom studies.
   d. Census, by sample survey, of window panes in the selected cities listed on pages 8 and 9.
   e. Evaluation of environmental parameters of material and building responses to natural phenomena.
   f. Theoretical study of critical earth structures.

3. An interdisciplinary group, including engineers and lawyers, should be appointed to study legal-structural considerations of commercial SST operations.

4. Contracts should be let to several competent companies specializing in instrument-data-recording-and-retrieval systems to propose the characteristics for an economical monitoring system, and to accomplish preliminary cost effectiveness analyses of the proposed system.