THE INITIATION OF PREMATURE BREAKUP OF RIVER ICE COVER:

EXISTING METHODOLOGIES AND APPROACHES TO INTEGRAL ANALYSIS

A.K. Abdel-Zaher

Graduate Student, Department of Civil Engineering
University of New Brunswick
P. O. Box 4400
Fredericton, New Brunswick E3B 5A3

K. S. Davar and J. L. Dawe

Professors, Department of Civil Engineering
University of New Brunswick
P. O. Box 4400
Fredericton, New Brunswick E3B 5A3

ABSTRACT

Premature breakup of river ice covers often leads to intensive ice runs, jams and damages from flooding. Normally, this type of breakup occurs in the spring. It starts with the formation of longitudinal cracks followed by transverse cracks in the ice cover and fragmentation of the entire ice cover in the final stages. This type of breakup is accompanied by severe damages in the vicinity of the river.

Analytical and forecasting models have been developed in order to predict such events. However, because of the multitude of factors which control such phenomena and the complexity of the processes involved a comprehensive model does not appear to exist for analyzing the integral action of the hydrodynamic forces and the structural resistance of the ice cover.

This paper presents a brief survey of the currently available models developed for predicting premature breakup of river ice covers. Further, the paper emphasizes the need for and presents an outline for experimental laboratory work, field programs for measuring the internal stresses before failure, field observations of crack configurations and the behavior of river ice as a material. Also, analytical approaches being currently developed for modelling the hydrodynamic-structural interaction leading to the premature breakup are briefly presented.

1. INTRODUCTION

The premature breakup of river ice covers often leads to intensive ice runs, jams, flooding and extensive damages (e.g. in the Saint John River, N.B., ice jam flooding results in about $7.8 million in damages per event). Premature breakup has been investigated by many researchers in order to predict its initiation and to avoid related damages. However, due to the multitude of factors which control the process (e.g. hydrologic, hydraulic, meteorologic, geomorphic, ...etc) in addition to the complexity of the hydrodynamic-structural interactions leading to premature breakup, no comprehensive model yet exists describing the process.

The existing methodologies are based on many assumptions and require extensive verification in the field. In addition, laboratory studies need to be done to simulate the integral hydrodynamic and structural behavior of ice covers.

This paper presents a brief survey of the currently available methodologies for analyzing the initiation of premature breakup. Also, the paper will outline approaches being currently developed to predict the initiation of the premature breakup based on integral behavior of the ice cover using the elastic theory of materials and finite elements analysis.

2. DESCRIPTION OF BREAKUP PROCESSES

The initiation of the breakup processes normally occurs when an ice covered river is subjected to mild weather conditions. Warm weather results in rapid snowmelt and may be accompanied by heavy rain. Accordingly, the discharge will increase underneath the intact ice cover causing an increase in uplift pressure and boundary frictional forces. This process results in formation of longitudinal cracks followed by transverse cracks due to a decrease in the strength of the ice cover to resist these forces. Once these cracks have formed, large ice floes are set in motion; these floes are eventually broken down into smaller fragments due to their repeated impacts with other floes or the river boundaries. This type of breakup has been defined as "premature breakup" (Deslauriers, 1968 and Beltaos, 1984b). It is most likely to occur rapidly, accompanied by severe damages in the vicinity of the river due to flooding.

The penetration of continuous intensive solar radiation into the ice cover is another hydrometeorological factor which plays a role in influencing the type of breakup process. When this is the dominant factor the ice cover dimensions and strength decrease causing disintegration of the ice cover mostly in place. In such cases transport of ice downstream results in insignificant damages. This type of breakup has been defined as "overmature or mature breakup" (Deslauriers, 1968 and Beltaos, 1984b). A breaking front is another type of breakup defined to exist if a short ice jam is resting upstream of an ice cover.

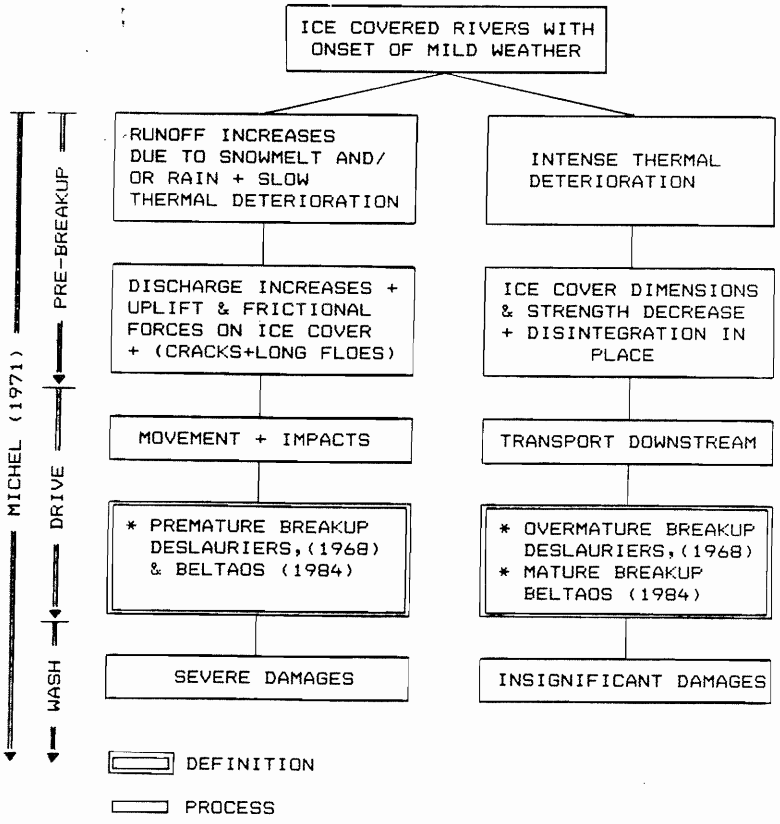


Fig. (1) Diagram for River Ice Breakup Processes

This paper addresses the integral analysis for an intact ice cover and the initiation of the cracking process in the premature breakup. Fig. (1) summarizes schematically the processes for the first two types of breakup and their definitions.

3. EXISTING METHODOLOGIES

The prediction of the initiation of premature breakup has been treated empirically (Shulyakovskii, 1963 and Beltaos, 1984a). These forecasting methods consider the river stage as an index to predict the initiation of the process and its severity at a specific site (e.g. the gauge on Nashwaak river at Durham Bridge, N.B.). The measurements for such methods need good historical records to be available to give acceptable results. Such measurements are difficult to obtain during the initiation of the breakup process.

Recently many analytical models have been developed to give a better understanding of the initiation of the premature breakup process. In the next two sections these models will be briefly presented and their limitations identified.

3.1. Analytical Models

The severity of the premature breakup event and related damages has encouraged many researchers to develop models to predict the initiation of the process. The path to these models started with an assumption that the intact ice cover attached to the banks is floating and elastically deformable, with uniform thickness across the full width of the river.

The application of the uplift pressure due to increase of river discharge in the spring with slow thermal deterioration is followed by longitudinal and transverse cracks in the ice cover. The structural equilibrium for the ice cover in such cases considers its own weight, buoyancy, deflection and uplift pressure Fig. (2) using the following equations:

$$P = p + \gamma\,(s_i h_i - w) - \gamma_i\, h_i. \qquad (1)$$

which reduces to $P = p - \gamma w$. (2)

Here, P = net upward pressure, p = uplift distributed pressure, γ, γ_i are unit weights of water and ice, s_i = specific gravity of ice, w = deflection of the ice cover, and h_i = ice cover thickness.

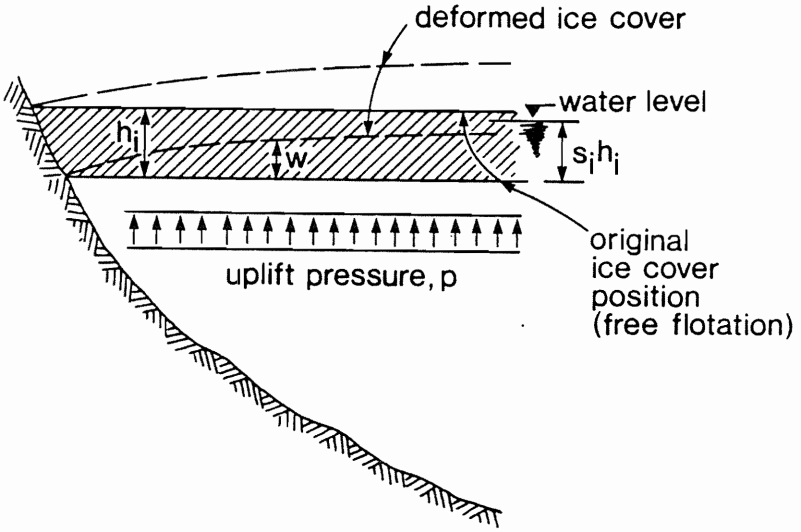


Fig. (2) Partial River Section with Ice Cover Subjected to Uplift Distributed Pressure p (Beltaos, 1985)

The form of equation (2) suggests that the ice cover may be treated as a plate on an elastic foundation with foundation modulus equal to γ, the unit weight of water (Hetenyi, 1946).

3.1.1. Models for formation of longitudinal cracks

Billfalk (1981) has investigated the initiation of longitudinal cracks. He introduced a simplification by using a transverse unit strip of the river instead of a plate, and considered the strip as a semi-infinite beam on an elastic foundation, neglecting the longitudinal change in the uplift pressure. Laboratory tests showed an agreement with the theory, but field tests deviated from the theoretical predictions.

Kozitskiy (1982) considered large to medium size rivers and viscoelastic behavior of the ice. He came up with a formula to predict the water level change required to cause longitudinal cracks. The study had good agreement with observations for one river. The formula seems applicable if reliable estimates of ice properties are available.

Beltaos (1984b and 1985) extended Billfalk's solution to a finite length and got good results for many observations. In addition, he proved that only one crack will form if $\lambda W < 3$ and the solution coincided with Billfalk's solution if $\lambda W > 6$, where λ is the system characteristic defined below and W is the river width. Fig. (3) shows an observation for one longitudinal crack. The parameter λ is defined by

$$\lambda = \sqrt[4]{\gamma/4EI}$$

where γ = unit weight of water, E = elastic modulus of ice, and I = moment inertia per unit cover width. Summary is given in table (1),

Fig. (3) Single Longitudinal Crack and Uplifted Strips Due to Rise in Water Level. Channel Width = 10 m (Courtesy of E. Kuusisto/Beltaos, 1985)

Christensen and Tryde (1986) investigated the uplift ice forces on long vertical walls due to rapid water level changes. The study considered a semi-infinite beam on an elastic foundation with fixed end only and took into account the shear forces for the cracked ice sheet. The study came up with a new formula for the water level change required to detach the ice cover. The magnitude of water level change in their study was about three times the values obtained by Billfalk and Beltaos. This study was conducted in a field of sea ice but it does emphasize the need for considering the shear effect for an initially cracked ice cover; this effect is very important in determining the eventual detachment for the central part of the ice cover. Also, it may clarify the delay in flooding above the ice cover after the longitudinal cracks form. All previous models are summarized in table (1).

3.1.2. Models for formation of transverse cracks

Many investigators have dealt with such cracks through observations and/or analytical models. These cracks initiate after the separation of the central part of the ice cover from the river boundaries. Two main factors are believed to cause such transverse cracking. The first one is the bending in a horizontal plane due to accumulation of shear forces underneath the ice cover at any bend. Shulyakovskii (1972) has defined such a case as shown in Fig. (4). The second one is the upward bending due to the sudden release of an ice jam and the consequent flood wave; Beltaos (1985) has defined such a case as shown in Fig. (5).

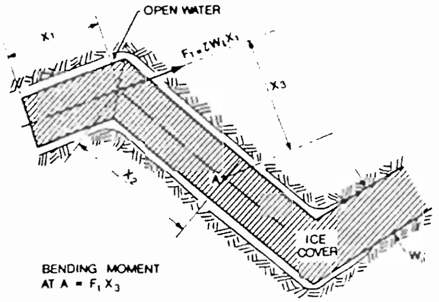


Fig. (4) Shulyakovskii's Mechanism of Transverse Crack Formation (Beltaos, 1984b)

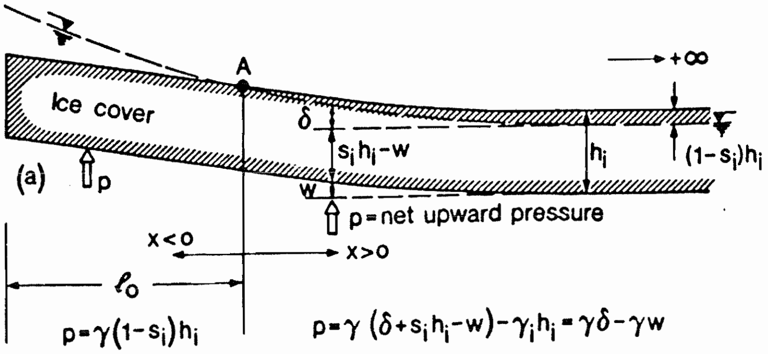


Fig. (5) Definition Sketch for Upward Bending Due to Sudden Release of an Ice Jam Upstream (Beltaos, 1985)

Nuttall (1970) has observed spacings of approximately 4 to 5 times the river width in N. Saskatchewan and Pembina Rivers. Shulyakovskii (1972) suggested that the accumulation of the shear forces and the down slope component of the ice cover weight can cause bending stresses leading to development of transverse cracks. Billfalk (1982) has shown that a steep wave is needed to cause upward bending for transverse cracking. The study used the semi-infinite beam on an elastic foundation theory and assumed linear water surface profile for the flood wave.

Kozitskiy (1982) dealt with this problem in two ways. In the first he considered an ice jam resting on the detached central part of the ice cover which behaves as a plate on an elastic foundation. The transverse cracks caused by buckling were observed with spacings equal to the width of the river; theoretical estimates confirmed such spacing to be equal to half wave length for buckling. For the second he defined a formula for the breakup condition in the case of a flood wave.

Beltaos (1984b and 1985) generalized Shulyakovskii's approach and supported the predictions for cracking by observations on the Thames River during the 1984 breakup event Fig. (6).

Also, Beltaos (1985) has proved by assuming a curved water surface profile for the flood wave and a semi-infinite beam on an elastic foundation that the transverse cracks by upward bending cannot occur by increase in stream flow due to snowmelt and/or rain only but possibly due to sudden release of an ice jam upstream. A summary for these models is given in table (1).

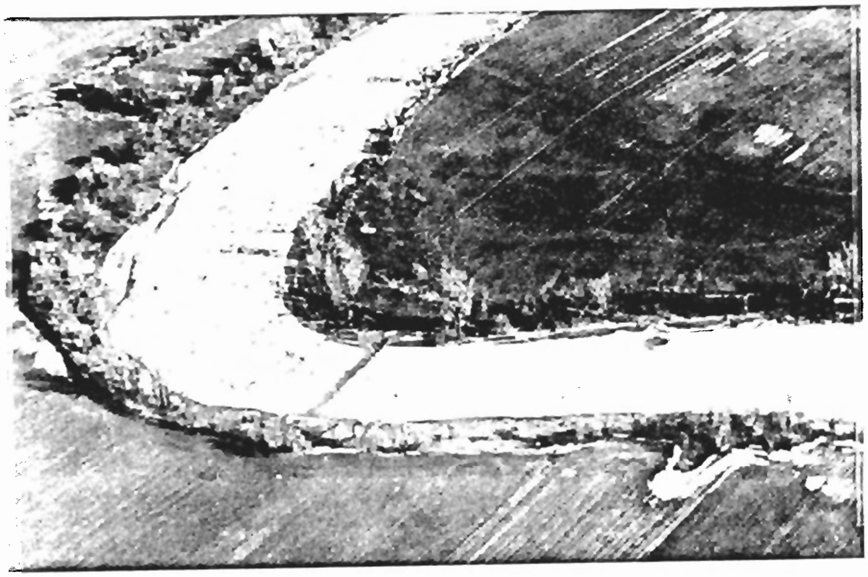


Fig. (6) Observed Transverse Crack, Thames River, Ontario, 1984 (by Beltaos)

3.2. Limitations

As mentioned earlier, many models exist for predicting the initiation of longitudinal and transverse cracks in the case of premature breakup. However, these models include many assumptions which can be limitations in developing a comprehensive model for analyzing the integral action of the hydrodynamic forces and the structural resistance of the ice cover. These limitations are summarized in the next two sections.

3.2.1. Limitations for analyzing longitudinal cracks

The limitations for analyzing longitudinal cracks may be summarized as follows:

1. In some models, only rapid water level changes causing uplift are considered.
2. In some models, the creep effects due to slow water level changes are included empirically by decreasing the ice strength and elastic modulus without rigorous quantitative evidence. This excludes Kozitskiy's analysis which considers linear viscoelastic behavior of ice; but he depends on an assumed value for ice viscosity. However, this assumption is not representative of ice which is non-linearly viscoelastic.
3. The thickened parts at the shore were not included in most of the analyses. This makes the assumptions concerning boundary conditions as fixed or hinged unclear. For example, Kozitskiy's observation for the cracks in the fixed-end case indicated that they occurred at some distance from the bank larger than normally observed.
4. Normally, uniform thickness is considered.
5. In nature, for long reaches of the river, the end conditions may not be symmetric and may be not longitudinally uniform due to irregularity (e.g. trees along the river boundary).

TABLE (1-A) MODELS FOR INITIATION OF THE PREMATURE BREAKUP

NO.	TYPE OF CRACK	RESEARCHER	WEATHER & PREDOMINATING ACTION	DISCHARGE	ICE COVER THICKNESS & TYPE	END CONDITION	THEORY	CRACK POSITION
1	LONGITUDINAL	* BILLFALK (1981)	ICE COVERED RIVER WITH ONSET OF MILD WEATHER & RUNOFF DUE TO SNOWMELT AND/OR RAIN	INCREASE	THIN OR THICK & ELASTIC	HINGED	SEMI-INFINITE BEAM ON AN ELASTIC FOUNDATION	$\pi/4\lambda$
2		* BILLFALK (1981)			THIN OR THICK & ELASTIC	FIXED		CLOSE TO THE SHORE
3		* KOZITSKIY (1982)			THIN OR THICK & VISCOELASTIC	FIXED	EQUILIBRIUM FOR TWO CANTILEVER AND STRAIGHT MID SPAN	RUNS SOME DISTANCE AWAY FROM THE SHORE AT H(CRACKED) = 0.8 H(SHORE)
4		* BELTAOS (1985)			THICK >.6 M & CREEP ACCOUNTED BY REDUCTION OF E AND σ_i	HINGED	FINITE BEAM ON AN ELASTIC FOUNDATION	MOST LIKELY EQUALS W/2
5		* BELTAOS (1985)			THIN →.1→.45M & CREEP ACCOUNTED BY REDUCTION OF E AND σ_i	HINGED		$\pi/4\lambda$
6		* BELTAOS (1985)			THIN OR THICK & CREEP ACCOUNTED BY REDUCTION OF E AND σ_i	FIXED		CLOSE TO THE SHORE

TABLE (1-B) MODELS FOR INITIATION OF THE PREMATURE BREAKUP

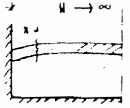
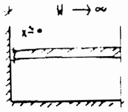
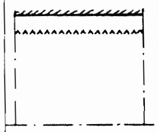
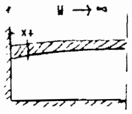
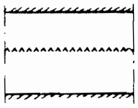
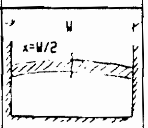
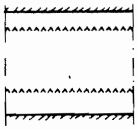
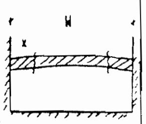
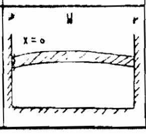
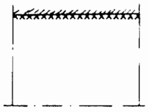
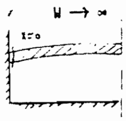
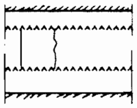
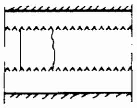
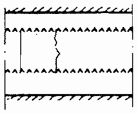
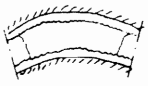
NO.	TYPE OF CRACK	RESEARCHER	CRACKING MODE (PLAN VIEW)	CRACKING MODE (SECTION)	BREAKUP(BUP) TYPE	OBSERVATIONS	REMARKS
1	LONGITUDINAL	* BILLFALK (1981)			PREMATURE BUP & SEVERE DAMAGES	* CURDE LABORATORY AND FIELD EXPERIMENTS TO SUPPORT THE THEORY	* E & σ_i CONST WITH RAPID CHANGE IN W.L.
2		* BILLFALK (1981)				NO OBSERVATIONS	* ASSUMED TO BE APPLICABLE IN OUTSIDE THICKEN PART AT SHORE
3		* KOZITSKIY (1982)				* SHELON RIVER (USSR) (1979)	* NEED RELATION BETWEEN CRACK POSITION AND ICE THICKNESS
4		* BELTAOS (1985)				* GRAND RIVER NEAR LEGGAT. * SEVERAL MANITOBA STREAMS. (CANADA)	* λW < 3 MOST CASES * FAIRLY WELL AGREEMENT WITH OBSERVATIONS.
5		* BELTAOS (1985)				* THAMES RIVER AT THAMESVILLE & NEAR LOUISVILLE. (ONT. - CANADA)	* IF λW > 6 →SEMI-INFINITE. * FAIRLY WELL AGREEMENT WITH OBSERVATIONS.
6		* BELTAOS (1985)				NO OSERVATIONS	* POSSIBLE IF ADHESION TO THE SHORE IS TOO LOW. * POSSIBLE IF NO CRACKS OBSERVED.

TABLE (1-C) MODELS FOR INITIATION OF THE PREMATURE BREAKUP

NO.	TYPE OF CRACK	RESEARCHER	WEATHER & PREDOMINATING ACTION	DISCHARGE	ICE COVER THICKNESS & TYPE	END CONDITION	THEORY	CRACK POSITION (X)
7	LONGITUDINAL	* CHRISTENSEN & TRYDE (1986)	ICE COVERED RIVER WITH ONSET OF MILD WEATHER & RUNOFF DUE TO SNOWMELT AND/OR RAIN	INCREASE	THIN OR THICK & ELASTIC	FIXED	SEMI-INFINITE BEAM ON AN ELASTIC FOUNDATION	OBSERVED TO OCCUR AT DISTANCE FROM .1-.5 FROM THE SHORE ≡ CLOSE
8	TRANSVERSE BY UPWARD BENDING	* BILLFALK (1982)			THIN OR THICK & ELASTIC	ALREADY DETACHED	SEMI-INFINITE BEAM ON AN ELASTIC FOUNDATION	$L(CR)=106\ d^{5/4}$
9		* KOZITSKIY (1982)			< 0.6 M & ELASTIC & ICE JAM U.S.		SEMI-INFINITE PLATE ON AN ELASTIC FOUNDATION& BUCKLING	OBSERVED TO OCCUR WITH SPACING OF HALF WAVE LENGTH FOR BUCKLING ` RIVER WIDTH
10		* BELTAOS (1985)			THIN OR THICK & ELASTIC		SEMI-INFINITE BEAM ON AN ELASTIC FOUNDATION	VARIED WITH THE LENGTH OF SUBMERGED PART AT ICE COVER EDGE
11	TRANSVERSE BY BENDING IN HL. PLANE	* BELTAOS (1985)					CRUDE ESTIMATE ACCORDING TO B.M. FROM U.S.SEGMENT (S) & B.M. FROM THE LAST SEGMENT	OBSERVED TO OCCUR WITH SPACING OF 1000 - 1600 ICE COVER THICKNESS

TABLE (1-D) MODELS FOR INITIATION OF THE PREMATURE BREAKUP

NO.	TYPE OF CRACK	RESEARCHER	CRACKING MODE (PLAN VIEW)	CRACKING MODE (SECTION)	REAKUP(BUP) TYPE	OBSERVATIONS	REMARKS
7	LONGITUDINAL	* CHRISTENSEN & TRYDE (1986)			PREMATURE BUP & SEVERE DAMAGES	DELAY FLOODING THAN EXPECTED	* ANALOGY FROM STUDY ON SEA ICE *LARGE VALUE FOR W.L CHANGE ABOUT 3 TIMES BILLFALK &BELTAOS
8	TRANSVERSE BY UPWARD BENDING	* BILLFALK (1982)		—		* D.S. STORNORRFORS POWER STATION * D.S. MALFORS POWER STATION (SWEDEN)	* LINEAR PROFILE FOR FLOOD WAVE WITH . HEIGHT < .9 d * NEED STEEP WAVE OR ICE JAM RELEASE
9		* KOZITSKIY (1982)		—		* SHELON RIVER (USSR) (1979)	* VALID IN CASE OF A FLOOD WAVE
10		* BELTAOS (1985)		—		NO OBSERVATIONS	*UNLIKLY TO OCCUR BY RUNOFF ALONE BUT POSSIBLE BY SUDDEN ICE JAM RELEASE. * CURVED PROFILE FOR A FLOOD WAVE
11	TRANSVERSE BY BENDING IN HL. PLANE	* BELTAOS (1985)		—		* THAMES RIVER (ONT. - CANADA) - MARCH (1982) - FEB. (1984) - MARCH (1984)	* POSSIBLE EVEN LOW FLOW SHEAR VALUES.

6. The position of the longitudinal cracks theoretically depends on the position of maximum bending moments. However, the eventual separation of the central part is affected by shearing effects due to interlocking, which has not been considered.

3.2.2. Limitations for analyzing transverse cracks

The limitations for analyzing transverse cracks may be summarized as follows:

1. The water surface profiles assumed for a flood wave, in the case of cracks caused by upward bending may need to be changed in order to confirm with the hydrodynamic equations of unsteady flow propagation.

2. The models assumed values of the flexural strength and elastic modulus pertaining to homogeneous and isotropic materials as required by elastic beam theory; this is not the case for natural river ice which consists of different layers (non-homogeneous) and may be anisotropic in any layer.

4. OUTLINE OF THE CURRENT WORK FOR INTEGRAL MODELLING OF PREMATURE BREAKUP

The integral modelling of the initiation of premature breakup has been started by the authors at U.N.B. This effort considers the joint action of hydrodynamic forces and the ice cover behaving as a structural unit.

The modelling process suggests the use of the finite element theory. The modelling will analyze selected lengths of river ice cover; these lengths will be analyzed as a beam on an elastic foundation and plate with in-plane stresses. The finite element modelling will use linear, quadratic, and cubic isoparametric serendipity elements for different discretizations. The use of finite element stress analysis will introduce the following features for a state-of-the-art structural analysis of the problem:

1. Comparison with the results of existing methodologies to examine their validity.

2. Use of non-uniform thicknesses for the ice cover, including thicker sections near the banks.

3. Variation of properties at different locations in the river ice cover.

4. Different end boundary conditions will be included in the analysis by varying the stiffness at the boundary (fixed symmetric, hinged symmetric, fixed-hinged, partially fixed symmetric, partially fixed-hinged, ...etc.).
5. The delineation of contours of maximum normal stresses and maximum shear stresses for the ice cover.

6. The finite element stress analysis can investigate the effect of changing the side friction for a free floating ice cover, after longitudinal cracks have formed. This will allow prediction of the penultimate stage of fragmentation in the central part.

5. EXPERIMENTAL AND FIELD WORK

Ice properties are very important from the point of view of their use in the structural-hydrodynamic analysis for initiation of the premature breakup process. The use of the finite element analysis requires flexural strength, strain modulus, uniaxial tension and compression strengths, to be determined from laboratory and field measurements. Since the suggested finite element analysis for the initiation of cracks will be verified in the cold room at U.N.B., preliminary laboratory tests have been performed to determine the flexural strength and the strain modulus.

5.1. Experimental work

The formation process is quite similar to the formation of S_1 ice as defined by Michel and Ramseier (1971).

5.1.1. Measuring ice properties

In order to determine the flexural strength and strain modulus a four-point load test for a simply supported beam was used. Such tests have been selected to investigate the bending effects and eliminate shear effects in the zone of maximum bending at the middle of the beam. The set-up consisted of an I-beam main frame with two adjustable cylindrical reaction bars welded to stiff distribution bars that could accommodate beams between 0.60 m and 2.0 m long. The load was applied at two points spaced a distance equal to one third the beam length; the load was applied by means of a manually operated screwjack, having 7850 N capacity Interface Model Gorner A/S - Load No. 126B.

The load cell was located between the screwjack and the load distribution channel with two adjustable cylindrical reaction bars and two stiff distribution bars. The central deflection of the ice beam was measured by a Dial Guage No. 25-481 attached to the main frame I-beam during the loading period. The maximum travel for the Dial Guage is 10 mm with a precision of ± 0.01 mm.

The length-to-width-to-thickness ratio for simply supported beams averaged 13:1:1. Flexural strength (σ) and strain modulus (E) were calculated from simple elastic beam theory using the following equations:

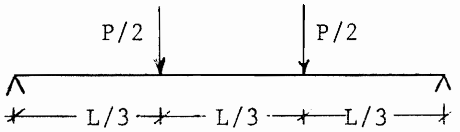


Fig. (7) A Definition Sketch for a Four Point Load Test

$$\sigma = \frac{P\ L}{W\ H^2} \tag{3}$$

$$\text{and } E = \frac{23}{108}\left\{\frac{P\ L^3}{d\ W\ H^3}\right\} \tag{4}$$

where: P = failure load,
L = distance between the two end supports,
W = beam width,
H = beam depth, and
d = the mid-point maximum deflection.

A group of 9 beams have been tested at a cold rood temperature of -6.4°C with different rates of loading. The results are shown in table (2). The plane of failure for those beams occurred between the two loading points which represents the maximum bending zone Fig. (8).

The last six tests were performed for a number of loading intervals, including a waiting period between 5-30 sec. to investigate the creep effect. The results are represented graphically in Fig. (10). It is seen that the last six beams behaved almost elastically. Also, no increase in the deflection occurred during the waiting periods for this type of ice, which indicated that the creep was minimal. It was observed for most of the beams that the flexural strength decreased with decreasing rate of loading and the strain modulus increased. But the flexural strength is independent of the strain modulus. The results agreed with Labrov's observations (1971). Also, the results agreed with Gow et al (1988) for S_1 ice which is similar in its structure to the beams tested.

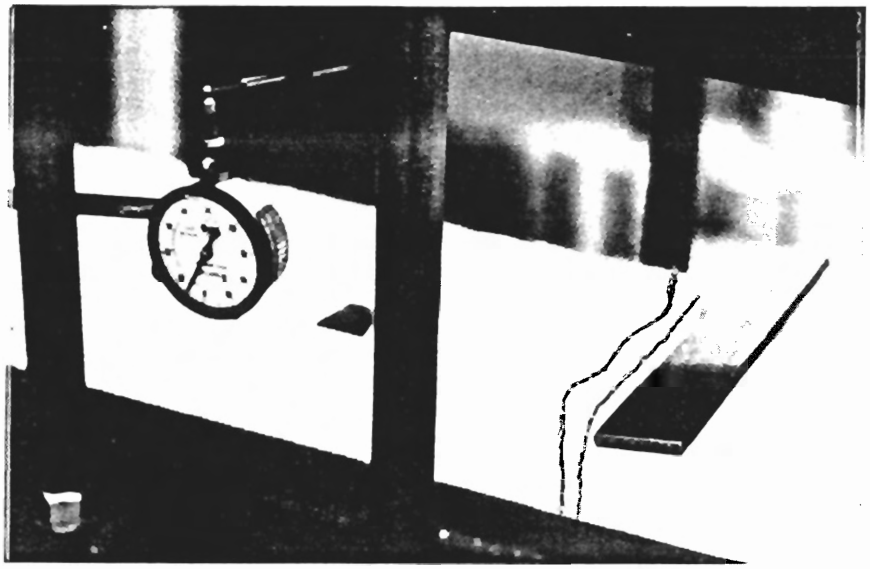


Fig. (8) Failure of an Ice Beam

TABLE (2) FLEXURAL STRENGTH AND STRAIN MODULUS

BEAM NO.	LOADING RATE (KN/SEC)	LONG (M)	WIDTH (M)	DEPTH (M)	FLEXURAL STRENGTH (KPa)	STRAIN MODULUS (GPa)
1	1.259	1.51	0.143	0.137	1063	6.278
2	0.370	1.9	0.149	0.140	1085	8.388
3	0.276	1.9	0.150	0.156	1058	6.142
4	0.230	1.9	0.150	0.149	1576	6.257
5	0.019	1.9	0.152	0.094	1961	6.247
6	0.094	1.9	0.153	0.150	815	4.748
7	0.094	1.9	0.152	0.147	909	6.337
8	0.094	1.9	0.153	0.152	1093	5.314
9	0.094	1.9	0.152	0.140	950	8.554

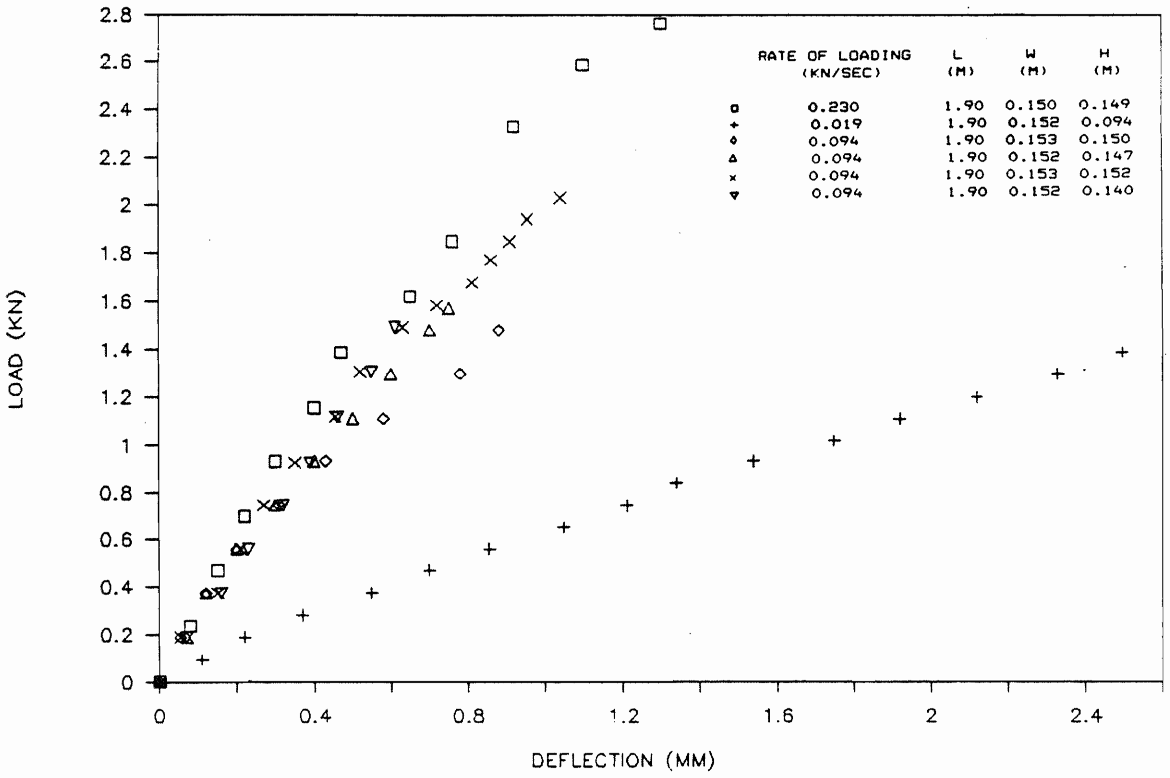


Fig. (9) Load-Deflection for Flexural Test With Different Rates of Loading

5.1.2. Laboratory ice cover fracture tests

The set-up will consist of a tank to investigate the fracturing of ice covers for different end conditions. A sketch for the ice fracture tank is shown in Fig. (11). The test results will be compared with the positions of longitudinal cracks in the case of a beam on an elastic foundation obtained from the theoretical finite element analysis. The uplift pressure will be simulated by imposing hydraulic pressure underneath the ice cover in the tank.

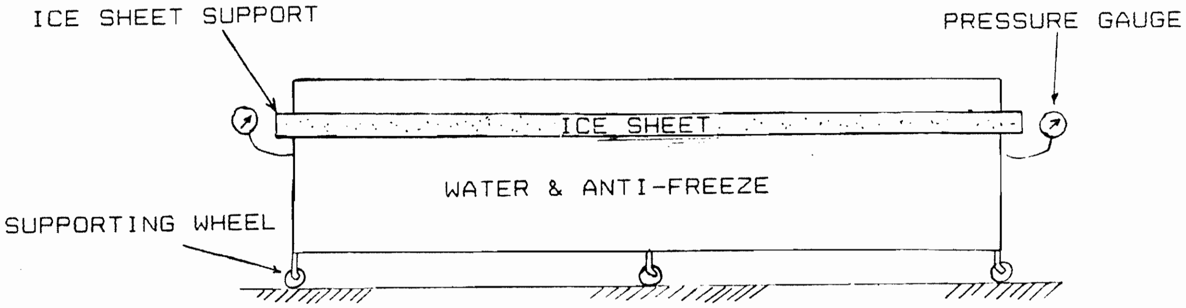


Fig. (10) Sketch for Ice Fracture Tank

5.2. Field observations and measurements

In winter 1990 observations for the initiation of breakup will be carried out on Nashwaak River, Saint John River, and Restigouche River, N.B. In addition, core samples will be obtained at different times after the complete formation of the ice cover and before the breakup; these samples will be used to determine uniaxial compression and tension strengths. Also, it is intended to install a monitoring device for the stress distribution in the ice cover for selected points.

These field observations and measurements will be used to verify for the analytical modelling by finite element method and its applicability to predict the initiation of premature breakup processes. Preliminary core samples have been extracted from Nashwaak River and its confluence with Saint John River, Fredericton, N.B. on March 15, 1989. It was noticed that at that time only the bottom layer of the river ice was undisturbed but the top layer of the ice cover consisting of porous granular material (about two-thirds of it) seems to have no strength at all.

6. CONCLUDING COMMENTS

The following concluding comments are presented based on the brief survey of the existing methodologies to analyze the initiation of the premature breakup and the outline for the current analytical, laboratory, and field work at U.N.B.

1. Most of the existing methodologies assumed the ice cover as a beam on an elastic foundation with steady uniform flow underneath.

2. The end conditions were assumed symmetrical (fixed or hinged) for longitudinal cracking.

3. Most of the existing methodologies assumed a uniform thickness for the ice cover and neglected the thicker part near the banks in analyzing the longitudinal cracks.

4. The assumed water surface profile for a flood wave in the case of transverse cracks affects the results of the analysis; the extent of such effects has not been clearly established.

5. The ice properties assumed for most of the methodologies were based on other sources.

6. The proposed finite element method will permit overcoming the shortcomings pointed out in many of the previous items.

7. The current analysis will be based on the elastic theory as suggested by the flexural strength tests conducted in the laboratory.

7. RECOMMENDATIONS

The following recommendations are made on the basis of this study:

1. More observations and documentation for the nature of the bank material and the degree of fixity are required.

2. More observations for the positions of longitudinal cracks need to be made.

3. Non-uniformity of the ice cover in thickness and strength should be considered in analyzing the premature breakup process.

4. Existence of bends in the river and their contribution to the premature breakup observations should be investigated.

5. The effects of non-uniform flow and uplift pressure distribution in the longitudinal direction should be considered.

6. The water surface profile for a flood wave may need to be changed to improve the predictions in case of transverse cracks.

8. ACKNOWLEDGEMENTS

The financial support for the current work at U.N.B. is from a grant awarded by NSERC to Prof. K. S. Davar, Department of Civil Engineering, University of New Brunswick.

9. REFERENCES

1. Ashton, G.D. (1981) "First Generation Model of Ice Deterioration" Proceedings of Conference on Frontier in Hydraulic Engineering, ASCE, Cambridge, Mass. p. 273-278.
2. Andres, D.D. (1988) "Breakup Prediction in a Non-Regulated River" Proceedings of Workshop on Hydraulics of River Ice/Ice Jams, Winnipeg, Canada.
3. Beltaos, S. and R. Lane, (1982) "Ice Breakup Characteristics of The Nashwaak River at Durham Bridge, N.B." NWRI, Hydraulics Division, Burlington, Ontario..
4. Beltaos, S. (1984a) "Study of River Ice Breakup Using Hydrometric Station Records" Proceedings of 3rd Workshop on Hydraulics of River Ice, Fredericton, N.B.
5. Beltaos, S. (1984b) "A Conceptual Model of River Ice Breakup" Canadian Journal of Civil Engineering, Vol. 1, No. 3.
6. Beltaos, S. (1984c) "River Ice Breakup", Proceedings, International Association for Hydraulic Research, International Symposium on Ice, Hamburg.
7. Beltaos, S. (1985) "Initial Fracture Patterns of River Ice Cover" NWRI Contribution #85-139, National Research Institute, Burlington, Ontario.
8. Billfalk, L. (1981) "Formation of Shore Cracks in Ice Covers due to Changes in the Water Level", Proceedings, International Association for Hydraulic Research, International Symposium on Ice, Quebec City.
9. Billfalk, L. (1982) "Break-up of Solid Ice Cover due to Rapid Water Level Variations" Report No. 82-3, Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.
10. Christensen, F.T. and P. Tryde, (1986) "Uplifting Forces on Long Vertical Walls" Proceedings, International Association for Hydraulic Research, Symposium on Ice, Iowa City, Iowa.
11. Deslauriers, C.E. (1968) "Ice Break-up in Rivers" Proceedings of a Conference on Ice Pressures Against Structures, NRC Technical Memorandum No. 92, p. 217-229.
12. Frederking, R. and F. U. Hausler (1978) " The Flexural Behavior of Ice From in Situ Cantilever Beam Tests" Proceedings, International Association for Hydraulic Research, Symposium on Ice, Lulea, Sweden.
13. Henderson, F.M. and R. Gerard (1981) "Flood Waves Caused by Ice Jam Formation and Failure" Proceedings, International Association for Hydraulic Research, International Symposium on Ice, Quebec.
14. Hetenyi, M. (1946) "Beams on Elastic Foundation" Ann Arbor, The University of Michigan Press.
15. Humes, T.M. and J. Dublin (1988) " A Comparison of The 1976 and The 1987 Saint John River Ice Jam Flooding With Emphasis on Antecedent Conditions" 5th Workshop on Hydraulics of River Ice/Ice Jams, Winnipeg, Manitoba.
16. Gow, A.J., H.T. Ueda, J.W. Govoni, and T. Kalafut (1988) "Temperature and Structure Dependence of The Flexural Strength and Modulus of Freshwater Model Ice" CRREL, Report 88-6, Hanover, New Hampshire.
17. Kozitskiy, I. Ye. (1982) "The Mechanism of Breakup of the Ice Cover of Rivers and Canals" Fluid Mechanics-Soviet Research, Vol. 11, No. 5.
18. Labrov, V.V. (1971) "Deformation and Strength of Ice" National Science Foundation, Washington, D.C.
19. Michel, B. and R. O. Ramseier (1971) "Classification of River and Lake Ice" Canadian Geotechnical Journal, Vol. 8.
20. Michel, B. (1971) "Winter Regime of Rivers and Lakes" Crops of Engineers, U.S. Army, Hanover, New Hampshire.
21. Michel, B. and R. Abdelnour (1975) "Breakup of Solid River Ice Cover" Proceedings, International Association for Hydraulic Research, Symposium on Ice Problems, Hanover, New Hampshire.
22. Nuttall, J.B. (1970) "Observations on Breakup of River Ice in North Central Alberta" Canadian Geotechnical Journal, Vol. 7.
23. Prowse, T.D. (1986) "Ice Jam Characteristics, Liard-MacKenzie Rivers Confluence" Canadian Journal of Civil Engineering, Vol. 13, No. 6.

24. Shulyakovskii, L.G./Editor (1963) "Manual of Forecasting Ice Formation for Rivers and Inland Lakes" Isreal Program for Scientific Translations, Jerusalem, 1966.
25. Shulyakovskii, L.G. (1972) "On A Model of The Breakup Process" Soviet Hydrology: Selected Papers, Issue No. 1.