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Strength and Deformation Modification Factors of Wood Based Composites for Engineering Design

Mizi Fan*,[1] and Vahik Enjily[2]

[1]Head of Research, Civil Engineering, School of Engineering and Design, Brunel University, UK

[2]International Director, Building Research Establishment, UK

Abstract: This paper summarizes some of the findings from a comprehensive study concerning the performance of wood based composites in building construction. The presentation only focuses on the strength and deformation modification factors for engineering design of wood based composites, that is, i) to determine whether the strength and deformation modification factors (k_{mod} and k_{def}) in Eurocode 5 for formaldehyde based boards are applicable to boards manufactured using new alternative binders such as isocyanate and cement, ii) to evaluate the effect of long-term concentrated loading by a full scale component test and small-scale indicative test, and iii) to examine the effect of long-term shear loading (panel and planar shears) on the performance of wood based composites for structural uses in comparison with long term bending loading in Eurocodes 1 and 5. Numerous results and important findings showed that i) the k_c and k_d values of isocyanate bonded particleboard (PB) under bending loads were lower than those of formaldehyde based PB, the former being 70-80% the latter; ii) the k_c of cement bonded particleboard (CBPB) were similar to that of formaldehyde based particleboards, but with the deflection of the former being about 1/5 the latter, the CBPB test pieces lasted much longer than MUFPB under duration of load tests; iii) stress modes had a significant effect on long term performance: The extrapolated k_c values under concentrated load were generally higher than those under bending load and in EC5, depending on the type of materials and joint profiles, the extrapolated k_d were very similar between concentrated and bending loads and in EC5, the extrapolated k_d values under shear load were higher than those in EC5, however, the k_c values varied considerably with the type of oriented strand boards (OSB) and medium density boards (MDF) under shear loading tests. The results clearly showed that there is a need for developing strength and deformation modification factors for new materials and materials under various stress modes for engineering designs.

INTRODUCTION

EN 1995-1-1:2004 Eurocode 5 (EC5) [1] uses a limit states approach to design (ultimate limit states and serviceability limit states). EC5 includes modification and partial safety factors that are applied to loads and material properties, i.e. the design values of properties shall be proportional to the characteristic values of the properties as described:

$$P_d = k\frac{P_k}{\gamma_M} \quad (1)$$

where, P_d is the design value of properties, P_k is the characteristic value of properties, k is the modification factor and γ_M is the partial factor for a material property, but does not include the actual loads and material properties themselves. Whilst guidance on the required loads is given in Eurocode 1 (EC1) [2], the user has to look elsewhere for many of the basic material properties.

Wood-based panels shall use the characteristic values given in the relevant European Standards, i.e. EN12369. EN12369-1 [3] includes characteristic values for i) oriented strand board (OSB), OSB/2, OSB/3 and OSB/4; ii) particle board, P4, P5, P6 and P7; iii) hardboard, HB.HLA2; iv) medium board, MBH.LA2 and v) medium density board (MDF), MDF.LA and MDF.HLS. EN12369-2 [4] includes characteristic values for plywood for structural design. When no values are given in European Standards, characteristic strength and stiffness values shall be calculated according to the method given in EN1058 and EN789 [5, 6].

Characteristic values have to be factored, i.e. by a duration of load factor k_{mod} and creep factor, k_{def}, to produce design values for wood based composites due to the nature of timber and timber products when subjected to sustained imposed loads [1, 7]: i) The increase in deflection with time (creep) and ii) The reduced loads, compared to those in short term tests, that can be sustained without failure over a prolonged period (duration of load). That is, the final mean values of modulus of elasticity, $E_{mean,fin}$, shear modulus $G_{mean,fin}$ and slip modulus, $K_{er,fin}$ shall be calculated as:

$$E_{mean,fin} / G_{mean,fin} / K_{ser,fin} = \frac{E_{mean} / G_{mean} / K_{ser}}{1 + k_{def}} \quad (2)$$

for serviceability limit states, and

$$E_{mean,fin} / G_{mean,fin} / K_{ser,fin} = \frac{E_{mean} / G_{mean} / K_{ser}}{1 + \psi_2 k_{def}} \quad (3)$$

for ultimate limit states.

*Address correspondence to this author at the Head of Research, Civil Engineering, School of Engineering and Design, Brunel University, UK; E-mail: FanM@bre.co.uk

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The design value of a strength, X_d and a resistance (load carrying capacity), R_d shall be calculated as:

$$X_d / R_d = k_{mod} \frac{X_k / R_k}{\gamma_M} \quad (4)$$

Where, X_k and R_k are the characteristic values of a strength and load carrying capacity respectively, and γ_M is the partial factor for a material property.

It can be seen that the factor k_{mod} effectively reduces the safe design loads that can be applied to a structure and is a function of material type, service class (environment), and load duration. The factor k_{def} increases the calculated deflection and is also a function of material type, service class and load duration.

EC5 includes values for both k_{mod} and k_{def} for a variety of wood-based products including various types of panels. However, these values were derived/agreed by the EC5 drafting committee based upon the limited test data available and entirely bending test data because of the lack of data in some areas.

This paper presents part of the finding from a complex project, which was:

- to determine whether the correct test methodology for wood-based composites is in place (Table **1**).
- to evaluate the suitability of the resulting data for use with Eurocodes 1 & 5 (Table **2**).

The presentation only focuses on the design modification factors for wood based composites. More information is presented in a series of separate papers [8-11].

2. MATERIALS AND METHODS

1. Materials

Commercially manufactured boards were used in all tasks relating to the above issues and these all conformed to relevant European product standards (Table **3**). Additionally, laboratory boards were manufactured so that all factors of production and furnish were kept constant when studying the performance of new materials. This allowed the strict comparison of performance.

2. Methods

Deformation Modification Factor/Creep Factor (k_{def})

The k_{def} was derived from creep testing in accordance with EN 1156. The creep test was carried out at 25% of the short-term failure load. The number of repetitions of each test set-up is 10. The duration of each creep test is 6 months.

The creep factor is defined as the ratio of the increase in deflection with time under load to the initial elastic deflection. The value of the creep factor will therefore change with time under load, level of stressing, and climate. It is dimensionless. The creep factor for a certain period of time t is given by:

$$k_c = \frac{(a_T - a_0) - (a_1 - a_0)}{a_1 - a_0} \quad (5)$$

here, a_T is the total deflection in millimetres at time t minutes; a_1 is the deflection in millimetres at 1 minute; a_0 is the deflection in millimetres of the unloaded test piece positioned in the creep test arrangement and $(a_1 - a_0)$ is the initial elastic deflection in millimetres as measured after 1 minute of load application.

Thus, each deflection measurement taken during the creep test is converted into a k_c value as shown above. The logarithm of the average of the values from the 10 test pieces for each time interval is plotted against the logarithm of time. A linear regression line is fitted through this data, excluding points from the first 10 minutes of the test (Fig. **1**).

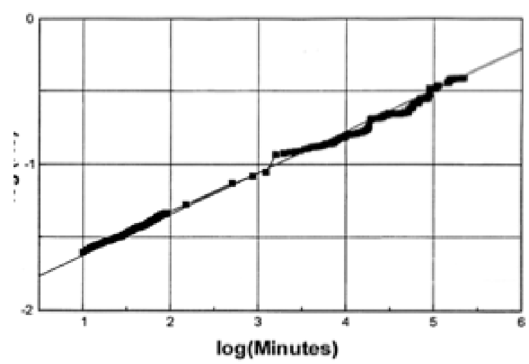

Fig. (1). Example of Log kc against Log (t) plotted for regression.

Table 1. Issues Concerned with "Is the Correct test Methodology in Place?"

Areas Involved	Issues Involved	Aims
EN789 Test methods for the determination of characteristic values	Bending, tension, compression, panel shear, planar shear – using medium size test pieces.	Confirmation on the suitability of EN789 for the determination of characteristic values.
EN310, EN319, EN321 [12-14] Small-scale test methods for quality control purposes.	All properties given as requirements in the EN material specifications	Confirmation as to whether or not the small-scale methods are suitable for controlling the production level of products with associated characteristic values derived in accordance with EN789.
EN12871, EN1195 [15, 16] Performance requirements, specifications and test methods for floors and roofs.	For floors and roofs, includes a soft body impact test and a concentrated load test. Also specifies the requirements in relation to EC1 & EC5.	Demonstration that typical constructions can continue to meet the requirements of EC1 and EC5.
EN1156 [17] Test method for determining creep and duration of load in bending.	Size of test pieces, edge sealing, sampling/matching procedures.	Proposal to use small, sealed specimens instead of semi-sized. Recommendations for improved sampling methods.

Table 2. Issues Concerned with "Is the Resulting Data Suitable for Use with EC1 & EC5?"

Areas Involved	Issues Involved	Aims
Conversion of creep and duration of load data to k_{def} and k_{mod} values.	The procedures used to analyse and extrapolate the data. The amount of data necessary to provide confidence in the modification factors.	Background information for the use of EN1156.
Consideration as to whether k_{def} and k_{mod} values derived from bending tests can also be used for other properties.	How do values vary with property and test method?	New procedures for assessing creep under other than bending loads.
EN1058 Derivation procedures for characteristic values.	Are the sampling requirements adequate? Is the calculation procedure suitable? Does the procedure result in adequate values for use with EC1/EC5.	Support for principles in EN1058.

Table 3. Panels and Corresponding Tasks

Panel/Type*	Thickness (mm)	EN Product Standard	Glue Type*
PB-com	19	EN312-7	MUF
PB-com	22	EN312-7	MUF
OSB-com	16	EN300-OSB/3	PF
MDF-com	18	EN622-5LA	MUF
MDF-com	22	EN622-5HLS	MDI
Plywood-com	16	EN636	PF
CBPB-com	18	EN634	Cement
PB-com	19	EN312-7	MDI
PB-lab	19	Fulfil EN312-7	MUF
PB-lab	19	Fulfil EN312-7	MDI
MDF-com	15	EN622-5LA	MDI
MDF-lab	19	Fulfil EN622-5LA	MUF
MDF-lab	19	Fulfil EN622-5LA	MDI
CBPB-com	18	EN634	Cement

*com = commercial products
lab = laboratory made board
MUF = melamine urea formaldehyde
MDI = methylenene diphenol diisocyanate
PF = phenol formaldehyde
PB=particleboard
OSB=oriented strand board
MDF=medium density fibreboard
CBPB=cement bonded particleboard

That is,

$$Logk_c = A + B\log t \tag{6}$$

Where, A and B is constant.

Then estimations of k_c for different load classes can made from this presentation format. The load classes include:

- Short-term (1 week)
- Medium term (6 months)
- Long term (10 years)
- Permanent (30 years)

Strength Modification Factor/Duration of Load Factor (k_{mod})

Unless specified, the determination of duration of load factors is carried out on a similar basis to the creep tests except that higher stress levels, which eventually lead to failure, are employed. A series of tests at stress levels of 55%, 60%, 65%, 70%, 75% and 80% of the short term failure load at 20°C/65%rh were used. At each stress level, 10 tests are carried out and the times to failure recorded. The mean time to failure is calculated and stress level is plotted against the logarithm of time to failure.

The duration of load factor for any given time t, is calculated from a linear regression line through the graph of stress level vs logarithm of time to failure, in the form given as:

$$\text{Log}_{10}\, t = c - m\, S$$

Where, c is the intercept on the vertical axis; m is the slope; S is the stress level (%); t is the time to failure (minutes) (Fig. **2**).

The load duration factor k_d is equal to the value S for any given time t.

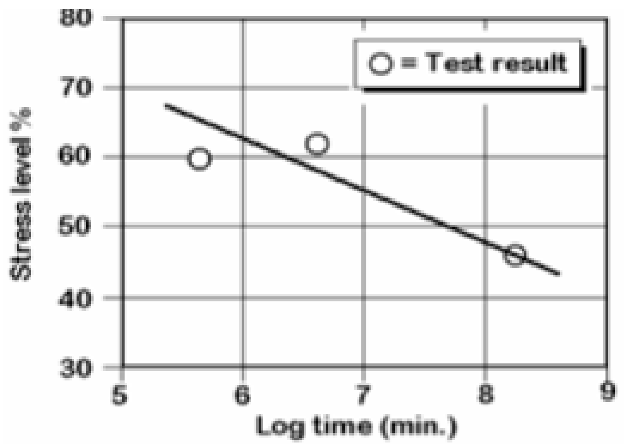

Fig. (2). Duration of load factor determination.

RESULTS AND DISCUSION

1. Strength and Deformation Modification Factors of New Materials

The majority of wood-based panels manufactured and used in Europe have formaldehyde based binders. There continues to be pressure to reduce the level of formaldehyde used in panels and this is being addressed both by altering the formulation of these adhesives and by seeking alternative adhesive systems. However, the large volume of data available concerning the behaviour of boards subjected to longer-term loads is based almost entirely on formaldehyde based binders. There is therefore a need to collect corresponding data on boards bonded with the alternative adhesives in order to confirm that the creep and load duration factors given in EC5 are appropriate to these materials.

Creep in Isocyanate Bonded Boards

It was found that for both the laboratory and commercial boards tested, the relative creep of isocyanate particleboard and MDF boards was generally lower than formaldehyde bonded boards tested under 20°C/65% relative humidity conditions (Figs. **3A**, **B**). The k_c of laboratory made MDIPB is only about 70% that of MUFPB and that of commercial MDIPB is about 80% that of MUFPB after six month loading. It is apparent that the performance of resin system is closely related to the long term performance of composites made. There is a similar trend for duration of load tests. Isocyanate bonded boards gave longer times until failure than corresponding formaldehyde boards.

It is considered that the values of k_{mod} and k_{def} contained in EC5 can be applied to isocyanate bonded MDF and particleboards although this is likely to be conservative.

Creep in Cement Bonded Particleboards

Commercial cement bonded particleboard (CBPB) was tested to determine the creep and load duration behaviour in bending. It is apparent that at 25% stress level, the k_c of CBPB was very similar to that of MUF bonded particleboard (MUFPB), while the deflection of CBPB was only about 25% of that of MUFPB because of its greater stiffness. An example of deflection with loading time is given in Fig. (**4**). The calculated kc after six month loading is 1.6 for commercial MUFPB, 1.5 for cement bonded particleboard, while the deflection is 5mm for MUFPB and 1.3 mm for cement bonded particleboard.

For duration of load tests, the test pieces subjected to stress levels of 45%, 50% and 55% had not failed after 9 months loading (Fig. **5**), with some test pieces being under load for 20 months at these levels. The duration of load behaviour at 60% and 75% stress levels was better than that of MUFPB. At 60% stress level, the shortest time until failure for CBPB was over 5 times the longest time to failure for MUFPB under the same conditions.

The evaluation of the creep and duration of load behaviour of isocyanate bonded and cement bonded particleboards suggests that it is safe to use the k_{mod} and k_{def} factors in EC5 with these materials. These factors may be unduly conservative. To exploit the potential of and efficiently use new materials, it is necessary to produce correct factors for engineering design.

The work confirms that the creep and duration of load behaviour of boards can be affected by the adhesive type used and it is therefore important that the long term behav-

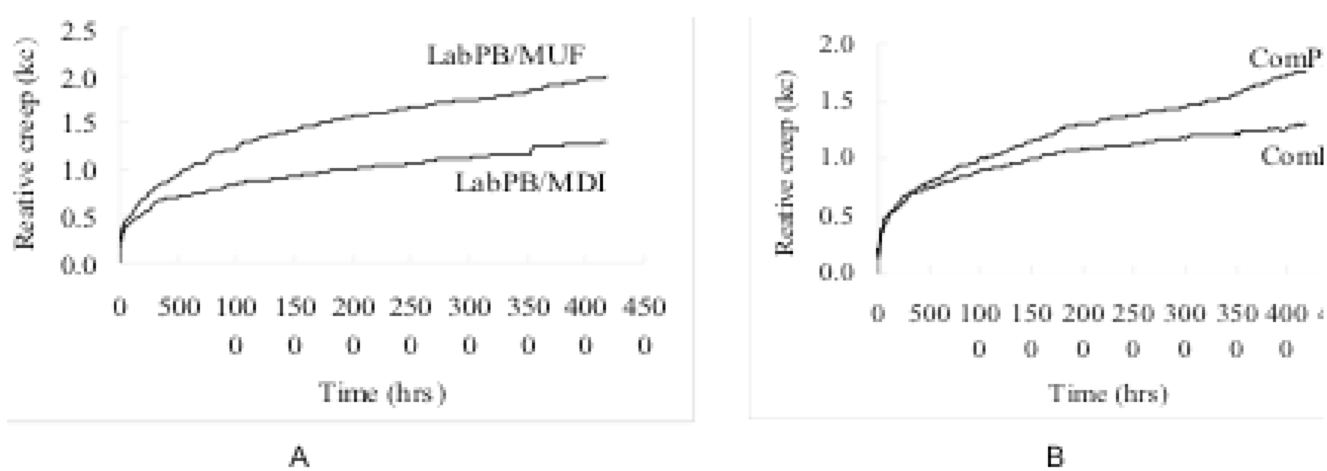

Fig. (3). Relative creep of MUFPB and MDIPB.

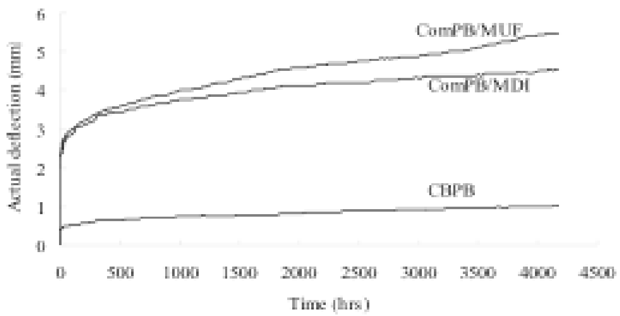

Fig. (4). Actual deflection of MUFPB and CBPB.

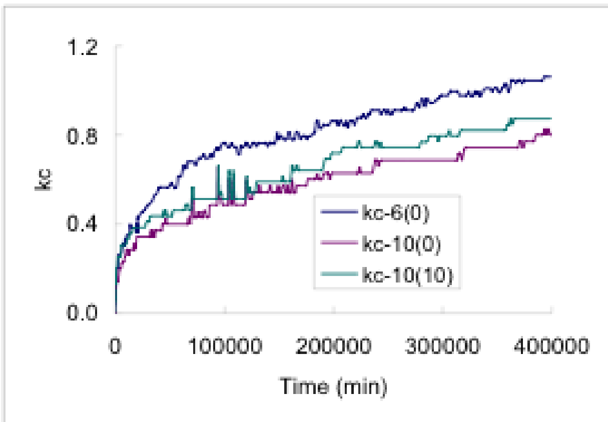

Fig. (5). Kc of CBPB loaded with different stresses (10(0)=45%, 10(10)=50% and 6(0)=55% stress level)

iour of boards made with new adhesives is evaluated before their use becomes widespread. In the two particular instances evaluated here any error in the factors in EC5 appears to lie on the side of safety but it cannot be guaranteed that this will always be the case.

2. Strength and Dformation Modification Factors Under Different Stress Modes

The values of k_{mod} *and* k_{def} included in EC5 were derived from the limited test data available which was entirely based on bending creep and/or duration of load tests and yet EC5 makes the assumption that these factors are appropriate to all stress types. This could include:

- bending
- concentrated loads
- tension and compression
- panel and planar shear

Moreover, the volume of data available from bending creep and duration of load tests is often considered to be too sparse to be able to set accurately the correct values of k_{mod} and k_{def} . Given the different stress forms and failure modes induced by the various forms of loading and the non-isotropic nature of wood-based panels, it is unreasonable to expect that the same k_{mod} and k_{def} values would be appropriate in all cases. Of the alternative loading conditions, shear and concentrated loads gave more cause for concern. Therefore, creep under concentrated loads and shear loads is presented below as an example to demonstrate the differences.

Concentrated Loads

The study of creep under concentrated loads included the development of a component-based test and small scale indicative test methods for measuring the creep and duration of load behaviour under concentrated loads. Semi-sized bending tests were carried out in parallel for comparison.

A component-based test method using a 1200mm square test piece and a small-scale method based on a 300mm square test piece were successfully developed. Both of these methods allow testing of solid and jointed panels. Having developed the methods, testing was carried out on particleboard, OSB, MDF and plywood. One stress level was used for creep (25%) and three stress levels (65%, 72% and 80%), for duration of load test. Testing was carried out on both solid and jointed test pieces at a climate of 20°C and 65% relative humidity.

The results are summarised in Figs. (**6**) and (**7**). It is apparent that the k_c values of plywood under concentrated load are higher than those measured under bending and in EC5, especially for long term values. And average kc for long- and permanent-term can be three times that of bending or in EC5. The extrapolated kc based on the test data for PB under concentrated load is lower than that under bending load except for small solid tests, however, the values are very similar to those in EC%.

The results for MDF are very similar between concentrated load, bending load and those in EC 5 except for small jointed test which has much higher extrapolated values for long term and permanent loading classes. The kc values for OSB are higher than those in EC5 but the average is similar to those under bending loads.

In general, the kd values are similar between concentrated load and bending load and those in EC5 (Fig. **7**).

A comparison of the k_{mod} and k_{def} values from the component and small-scale tests is shown in Tables **4** and **5**. It can be concluded that the component test developed is effective and that the small-scale test gives a good indication of likely results under the component test. Whilst the level of testing has not been sufficient to define k_{mod} and k_{def} for concentrated loads, there does not appear to be a safety problem with the use of the current EC5 values with concentrated loads. There is a suggestion that the k_{mod} values in EC5 may be too low for concentrated loads, but further testing would be required to confirm this.

Shear Loads

The estimation from the experimental results under long term shear loading has also been compared to creep factors given in Eurocode 5 for the relevant panel types, service class 1, (Figs. **8** and **9**). Creep results showed that the values from experimental results are different from the values laid down in Eurocode 5. In general, for MDF under panel shear load: $k_c < k_{def}$; for OSB under panel shear load: $k_c > k_{def}$; for MDF under planar shear load: $k_c > k_{def}$; for OSB under planar shear load: $k_c > k_{def}$.

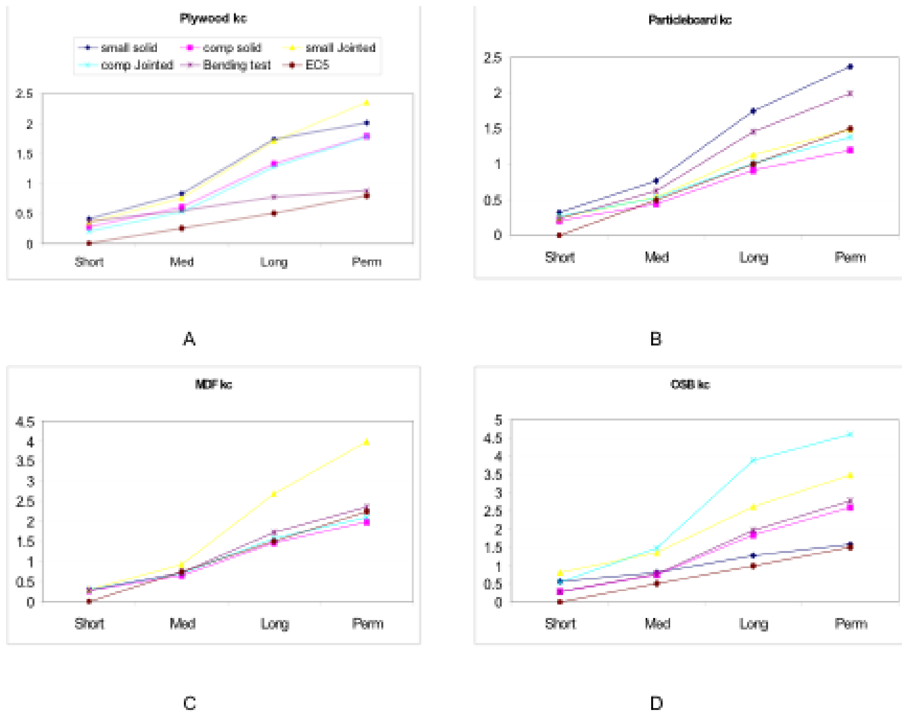

Fig. (6). Comparison of kc values from concentrated load, bending load and EC5.

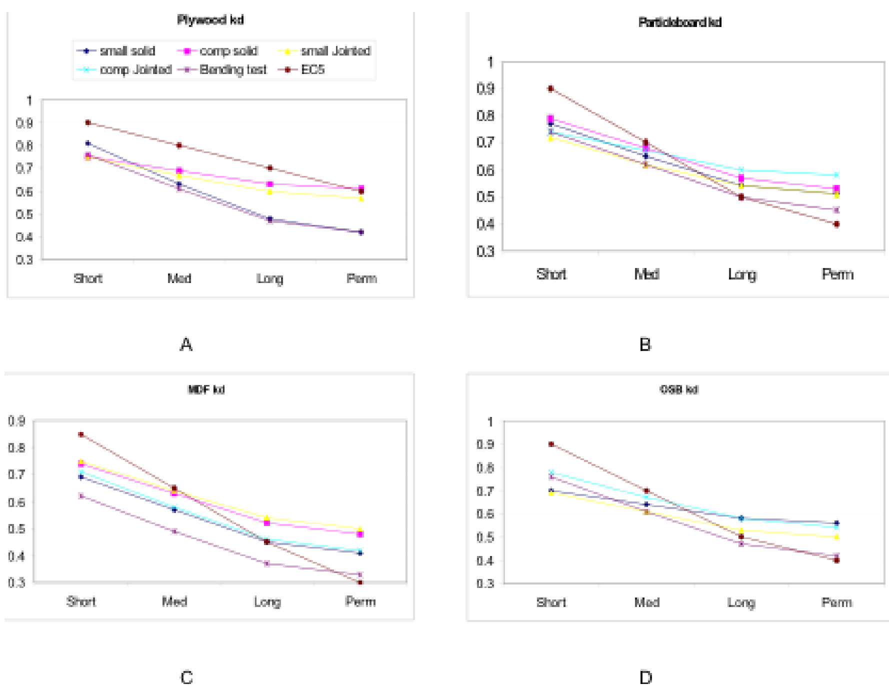

Fig. (7). Comparison of kd values from concentrated load, bending load and EC5.

It should be noted that the values in EC5 are for bending creep. It has proved that they are not suitable for shear creep, and this means that new k_c has to be developed for inclusion in Eurocode 5 for shear creep loading.

Duration of load of test showed that the values from experimental results are different from the values laid down in Eurocode 5. In general, for all the materials tested under both panel and planar shear loading, $k_d < k_{mod}$ for the short term and medium term, while $k_d > k_{mod}$ for the long term and permanent term. Again, it should be noted that the values in EC5 are arisen from bending creep tests. The results have proved that they are not suitable for shear creep loading and new characteristic values should be developed for shear loading design.

Table 4. Comparison of Calculated k_c for Component and Small Scale Test

Test type	Duration	Creep Factor k_c (k_{def})							
		Short		Med		Long		Perm	
	Material	S	EC5 SC1	S	EC5 SC1	S	EC5 SC1	S	EC5 SC1
Component test	Plywood	0.27	Bending test	0.61	Bending test	1.33	Bending test	1.79	Bending test
	PB	0.20		0.44		0.92		1.20	
	MDF	0.27		0.65		1.46		1.98	
	OSB	0.28		0.75		1.85		2.59	
Small-scale test	Plywood	0.41	0	0.83	0.25	1.74	0.50	2.01	0.80
	PB	0.32	0*	0.76	0.50*	1.75	1.00*	2.37	1.50*
	MDF	4.00	0	9.67	0.75	22.0	1.50	29.8	2.25
	OSB	0.56	0**	0.80	0.50**	1.28	1.00 **	1.57	1.50 **

Key : S = solid, Short = 1 week, Med = 6 months, Long = 10 years, Perm = 30 years,
*for P7 value, ** for OSB3

Table 5. Comparison of Calculated k_d for Component and Small Scale Tests

Test type	Duration	Load Duration Factor k_d (k_{mod})							
		Short		Med		Long		Perm	
	Material	S	EC5 SC1	S	EC5 SC1	S	EC5 SC1	S	EC5 SC1
Component test	Plywood	0.75	Bending test	0.69	Bending test	0.63	Bending test	0.61	Bending test
	PB	0.79		0.68		0.57		0.53	
	MDF	0.74		0.63		0.52		0.48	
	OSB	0.57		0.93		1.26		1.38	
Small-scale test	Plywood	0.81	0.90	0.63	0.80	0.48	0.70	0.42	0.60
	PB	0.77	0.90*	0.65	0.70*	0.54	0.50*	0.51	0.40*
	MDF	0.69	0.85	0.57	0.65	0.45	0.45	0.41	0.30
	OSB	0.70	0.90**	0.64	0.70**	0.58	0.50**	0.56	0.40**

Key : S = solid, Short = 1 week, Med = 6 months, Long = 10 years, Perm = 30 years,
*for P7 value, ** for OSB3

A comparison of relative creep data from bending, panel and planar shear tests suggests that there is a need for separate k_{def} values in Eurocode 5 for bending, panel shear and planar shear stresses for each panel type.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations can be presented as follows:

1. The creep and duration of load tests were studied and indicative strength and deformation modification factors were developed for the boards manufactured using new alternative binders (isocyanate and cement), and the wood based composites under shear loading (panel and planar shears) and concentrated loading.
2. The creep and load duration behaviour of boards could be affected by the adhesive types used. The partial evaluation of the creep and duration of load behaviour of isocyanate and cement bonded particleboards suggested that it is safe to use the k_{mod} and k_{def} factors in EC5 with these materials. The k_c and k_d values of isocyanate bonded particleboard (PB) under bending loads were lower than those of formaldehyde based PB. The k_c of cement bonded particleboard (CBPB) were similar to that of formaldehyde based particleboards, but with the deflection of the former being about 1/5 the latter, the CBPB test pieces lasted much longer than MUFPB under duration of load tests. However, the values in EC5 are neither accurate nor beneficial for both panel and construction industries.
3. Stress conditions were closely related to the creep and duration of load. The extrapolated k_c values under concentrated load were generally higher than those under bending load and in EC5, depending on the type of materials and joint profiles, the extrapolated k_d were very similar between concentrated and bending loads and in

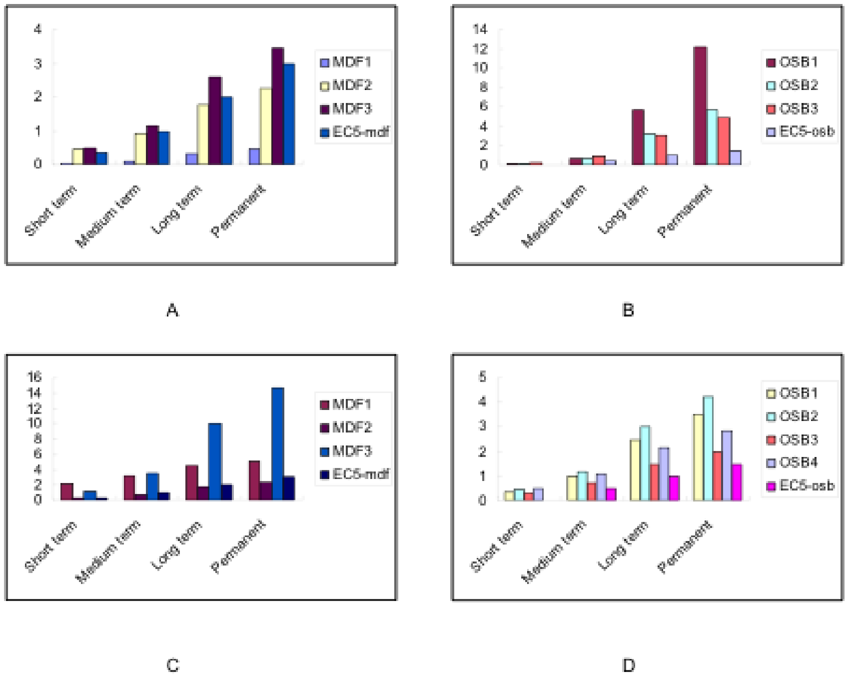

Fig. (8). A comparison of kc with kdef in EC5 for MDF and OSB under panel and d planar shear loading (**A** and **B**-panel shear, **C** and **D**-planar shear).

EC5, the extrapolated k_d values under shear load were higher than those in EC5.

4. The k_c values varied considerably with the type of oriented strand boards (OSB) and medium density boards (MDF) under shear loading tests. For MDF under panel shear load: $k_c < k_{def}$; for OSB under panel shear load: $k_c > k_{def}$; for MDF under planar shear load: $k_c > k_{def}$; for OSB under planar shear load: $k_c > k_{def.}$ For all the materials tested under both panel and planar shear loading, $k_d < k_{mod}$ for the short term and medium term, while $k_d > k_{mod}$ for the long term and permanent term.

5. The k_{mod} and k_{def} factors in EC5 factors may be unduly conservative with isocyanate and cement bonded particleboards. Further research should be carried out to de-

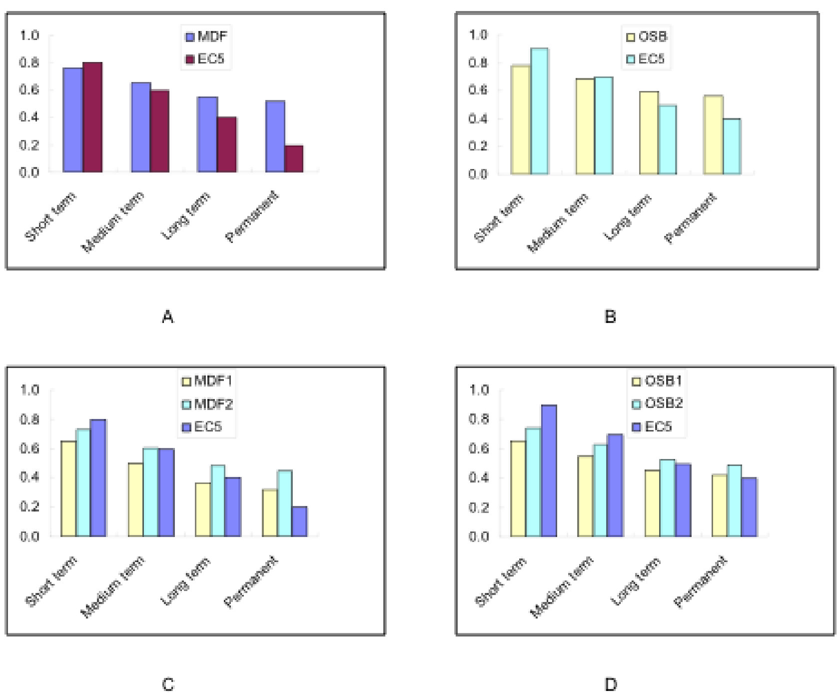

Fig. (9). A comparison of mean kd to kmod in EC5 for MDF and OSB under pannel and planar shear loading (**A** and **B**-panel shear, **C** and **D**-planar shear).

termine the correct k_{mod} and k_{def} for new materials, and the wood based composites under different stress and environmental conditions for engineering designs.

REFERENCES

[1] EN1995-1-1: Eurocode 5 - Design of timber structures. Part 1-1: General rules and rules for buildings, 2004.

[2] EN1991-1-1: Eurocode 1-Actions on Structures, 2002.

[3] EN12369-1: Wood based panels: Characteristic values for structural design, 2001.

[4] EN12369-2: Wood based panels: Characteristic values for structural design, 2004.

[5] EN789: Timber structures: Test methods – Determination of mechanical properties of wood-based panels, 1996.

[6] EN1058: Wood-based panels – Determination of characteristic values of mechanical properties and density, 1995.

[7] M. Fan, "Non-destructive systems for stress determination for long term (time dependent) creep loading", *Journal of Wood Science*, vol, 17(3), pp. 159-170, 2006.

[8] M. Fan, P. Bonfield, "Wood based Composites-Material parameters and specifications", in Proceedings 8th European Panel Products Symposium, 2004.

[9] M. Fan, "Effect of size on rheological behaviour of plant based composite materials", *ASCE Journal of Engineering Mechanics,* vol, 132(8), pp. 815-844, 2006.

[10] BRE: An integrated study of the long-term performance of wood based panels in floor and roof construction: Final report for EC project, 1998.

[11] BRE: Enhancing the efficiency and competitiveness of wood-based panels in construction: Final report for EC project, 2003.

[12] EN310, Wood-based panels. Determination of modulus of elasticity in bending and of bending strength, 1993.

[13] EN319, Particleboards and fibreboards. Determination of tensile strength perpendicular to the plane of the board, 1993.

[14] EN321, Wood-based panels. Determination of moisture resistance under cyclic test conditions, 2002.

[15] EN12871, Wood-based panels. Performance specifications and requirements for load bearing boards for use in floors, walls and roofs, 2001.

[16] EN1195, Timber structures. Test methods. Performance of structural floor decking, 1998.

[17] ENV 1156: Wood based panels-Determination of duration of load and creep factors, 1997.

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